Evaluation of the Barber-Colman Wetox Process for Sewage Sludge Disposal

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on Great Lakes Water Quality

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EVALUATION OF THE BARBER-COLMAN WETOX PROCESS FOR SEWAGE SLUDGE DISPOSAL

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ABSTRACT

An investigation was carried out to evaluate the suitability of the Barber-Colman Wetox process for municipal sewage sludge disposal. Technical and economic data for the Wetox process were gathered through literature, special correspondence, pilot plant visits as well as some experimental and analytical work performed at the Ontario Research Foundation (ORF) laboratory. These Wetox data were then analysed and compared with those of other sludge disposal methods. Particular emphasis was placed on the comparison between the Wetox process and the Zimpro process since they are rather similar in operation.

Based on the evaluation of a limited amount of laboratory and pilot plant data, it appears that the Wetox process is simple to operate at $450^{o}F$, 600 psi ($\sim 232^{o}C$, 4137 kPa) with 0.3% sulphuric acid. The process is suitable for sewage sludge disposal, although no commercial scale Wetox plant has yet been built. Furthermore, Wetox can achieve similar sludge destruction efficiency, i.e. approximately 80% destruction of suspended solids and 65-82% reduction in COD, but at a lower temperature and pressure than the corresponding Zimpro process. This is believed to be due to the design of the Wetox reactor, which ensures adequate oxygen transfer into the sludge, as well as the addition of a small amount of sulphuric acid to speed up the oxidation.

For larger scale sludge disposal (e.g. 100 tons or $\sim$ 91 metric tons dry solids per day), the total disposal cost (i.e. from digested sludge to ultimate land disposal), on per ton dry solids basis, via the Wetox process can be as low as \$21 ($\sim$ \$23 per metric ton) if the plant is run under the most favourable conditions at full capacity. Realizing that only the major expenditure items are included in the cost estimates and other "hidden" costs may exist, the estimated cost of \$21 is judged to be only approximate and probably low. Nevertheless, it does put the cost of the Wetox process into perspective. By comparison, the sludge disposal cost via the Wetox is substantially lower than via the high temperature-pressure Zimpro process. The Wetox cost is at least competitive with the low temperature-pressure Zimpro route as well as with other more conventional sludge disposal processes.

It is also noted that the Wetox process may have high potential for sludge disposal in small communities where land spreading is unsuitable.

Because only a limited amount of laboratory and pilot plant Wetox data are available, the aforementioned conclusions should be viewed as tentative until they can be verified with data obtained by further experimentation.

RÉSUMÉ

On a mené une étude afin d'évaluer la capacité du procédé Barber-Colman Wetox (de combustion humide des boues en milieu acide) pour l'élimination des boues provenant des eaux usées municipales. On a réuni les données techniques et économiques relatives à ce procédé à partir de publications, de correspondance spéciale, de visites d'usines pilotes et de travaux expérimentaux et d'analyse effectués dans les laboratories de l'Ontario Research Foundation (ORF). Ces renseignements ont ensuite été analysés et comparés avec les données obtenues à partir d'autres méthodes d'élimination et d'évacuation des boues. On a comparé plus particulièrement le procédé Barber-Colman et le système Zimpro car ils ont un fonctionnement plutôt similaire.

D'après l'étude d'une quantité limitée de données recueillies en laboratoire et en usine pilote, il semble que le procédé Barber-Colman soit d'application simple à 450^{o} F et à pression de 600 lbs/po^{2} (environ 232^{o}C, 4137 kPa) en milieu contenant 0.3% d'acide sulfurique. Ce procédé, quoique recommandable pour l'élimination des boues des eaux usées n'est pas encore utilisé à l'échelle industrielle. De plus, l'efficacité de l'élimination des boues par ce procédé, c'est-à-dire une élimination d'environ 80% des matières en suspension et une réductions de 65% à 82% de la demande chimique d'oxygène (DCO), mais à température et pression moins élevées, se compare à celle du système Zimpro. On croit que ces résultats sont attribuables à la forme du réacteur Wetox qui procure aux boues une alimentation appropriée en oxygène et à l'addition d'une petite quantité d'acide sulfurique accélérant l'oxidation.

Si l'évacuation des boues se fait en quantités plus importantes (100 tonnes ou environ 91 tonnes métriques de matières sèches par jour), et si l'usine fonctionne à plein rendement et à conditions favorables, le coût global du traitement (c'est-à-dire, de la digestion des boues jusqu'à la décharge) utilisant le procédé Barber-Colman, peut se situer à $21 par tonne de matières sèches (environ $23 par tonne métrique). Étant donné que l'estimation du coût ne comprend que les dépenses principales et non les dépenses "cachées", nous croyons que le montant de $21 ne constitue qu'une approximation probablement faible du coût réel. Néanmoins les coûts

d'opération du procédé Wetox méritent de l'attention. Ce coût est passablement moins élevé que celui de système Zimpro qui utilise des températures et des pressions élevées. Enfin, il se compare au système Zimpro qui utilise des températures et des pressions basses, de même qu'aux procédés plus classiques d'évacuation des boues.

On fait aussi remarquer que le procédé Wetox peut très bien servir à l'évacuation des boues provenant de petites localités où l'épandage des déchets ne convient pas.

À cause de la quantité limitée de données provenant du laboratoire et de l'usine pilote qui utilisent le procédé Wetox, les conclusions précédentes devraient être considérées comme provisoires jusqu'à ce qu'elles soient confirmées par des études plus approfondies.

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CONCLUSIONS

The evaluation of the Barber-Colman Wetox process is comprehensively summarized in Table 1. In the same table, comparisons are made between the Wetox and the Zimpro processes. Based on this information it appears that the Wetox process is simple to operate and suitable for sewage sludge disposal. Furthermore, it appears that Wetox alone (i.e. without lime treatment) can achieve similar sludge destruction efficiency but at a lower temperature and pressure than the corresponding Zimpro process. This is probably due to the design of the Wetox reactor, which ensures adequate oxygen transfer into the sludge, as well as the addition of a small amount of sulphuric acid to speed up the oxidation.

For large scale sludge disposal (e.g. 100 tons or $\sim$ 91 metric tons dry solids per day), the total disposal cost (i.e. from digested sludge to ultimate land disposal), on per ton dry solids basis, via the Wetox process is substantially less than via the high temperature-pressure Zimpro process. The Wetox process is at least competitive in cost with the low temperature-pressure Zimpro route as well as with other most common conventional sludge disposal processes, all of which cost approximately \$30 per dry ton ($\sim$ \$33 per metric ton).

For small scale sludge disposal operation, the economics of the Wetox process (although more expensive in small scale than large scale operation) may be even more favourable as compared to other conventional processes. This is particularly true for small communities with wastewater treatment plants where land spreading of sludge is unsuitable because of political, geological or climatic reasons. The Wetox process is easier to operate than the high temperature-pressure Zimpro process and it involves less process steps than most of other conventional processes including the low temperature-pressure Zimpro-dewatering-incineration combination. Consequently, the capital and operating cost of the small scale package Wetox process may be considerably less than other processes at similar scale. For a really small size Wetox system (e.g. 6 tons or $\sim$ 5.4 metric tons solids per day), semi-batch units may be used and further cost savings may be realized. Alternatively, small scale continuous or semi-batch units may be designed to operate at slightly higher temperature-pressure, say 485^{o}F and 750 psi ($\sim$ 252^{o}C, 5171 kPa), without too much increase

in cost but may improve the destruction efficiency by approximately 10%. Such a possibility should also be investigated.

It must be stressed again at this point that the aforementioned conclusions are based on comparing the limited amount of Wetox pilot plant performance data with the commercial plant operating data of Zimpro as well as other processes. Actual scale-up of the Wetox process may alter the sludge destruction efficiency and hence the cost. At any rate, more experimental work and the development of hardware such as heat exchangers, pumps, stirrer-drive, etc., will be required before Wetox plants can be commercialized.

TABLE 1. WETOX VERSUS ZIMPRO FOR SEWAGE SLUDGE DISPOSAL.

DIFFERENCES	WETOX		
	Features	Advantages	Disadvantages
Reactor design	• Agitated	Improve heat and mass transfer between gas-liquid-solid phases for efficient reaction. Prevent accumulation of solids inside the reactor	Need extra stirrers, motor and drive, thus increasing capital and operating costs
	• Compartmented	Minimize short circuiting	Baffles inside the reactor are difficult to install or repair. Pumping cost also increases
	• Horizontal	Lower erection cost and easier accessibility to maintenance. Safer operation and more aesthetic	Occupy more plant space
	• Titanium reactor or steel shell with brick lining for large reactor	Chemical resistant and better heat insulation	Costly material of construction
Operation	• Acidic medium	Improve the rate and the extent of sludge oxidation. Eliminate equipment scaling problem	Chemical dosage increases capital and operation costs and necessitates the subsequent lime treatment. Sulfate loading in the sewage plant effluent will also increase
	• Phase separation at the reactor	Increase the effective retention time of sludge inside the reactor. Concentrate the pollutants in the liquid effluent stream for efficient removal via lime neutralization	Need separate heat exchangers for the liquid phase and the vapor phase Wetox effluents
	• Post-treatment (Wetox plus lime treatment is marketed as "Puretec System")	Necessary step to neutralize free acid. Remove heavy metals, phosphates, ammonia, residual suspended solids and part of sulfates	Capital cost and operating cost of lime treatment plus the clarifiers
Performance	• 450°F ($\sim$ 232°C) 600 psi, ($\sim$ 4137 kPa) 3 gm per litre of sulfuric acid in sludge and 40-60 minutes of retention time	65-82% organic oxidation, 80% suspended solid destruction. Lower temperature-pressure system, therefore lower capital and operating cost. Destruction efficiencies are similar to that of high temperature-pressure Zimpro process. Reaction is self-sustaining	Extra cost on agitation, baffles, acids, heat exchangers and lime-treatment etc.
Complete	• Wetox effluent is neutralized and pumped into a nearby lagoon for settling of solids, supernatant liquor from lagoon is recycled to secondary treatment plant	75-85% organic destruction, approx. 90% solid destruction possible. Relatively simple process; easier to operate than the high temperature-pressure Zimpro process and involve less process steps than the low temperature-pressure Zimpro process. May be very suitable for small community where land spreading of sludge is impractical	No commercial plant has yet been built. Non-condensable gases may have to be incinerated before discharge to atmosphere
Total cost for sludge disposal via the complete disposal system	Estimated cost for 50 tons ($\sim$45 metric tons) dry solids per day plant operating at full and at half capacity is $31 and $55 respectively per ton dry solids (~$34 and $61 per metric ton dry solids). Estimated cost for 100 tons ($\sim$91 metric tons) dry solids per day plant operating at full and at 60% capacity is $21 and $30 respectively per ton dry solids (~$23 and $33 per metric ton dry solids).		

TABLE 1. (Continued)

ZIMPRO		
Features	Advantages	Disadvantages
• Vertical	Compact and occupy a minimum of plant space	Vertical reactor and heat exchangers (30-80 feet or ∿ 9-24 meters tall) contribute difficulties to installation and maintenance
• Tower	Simple Construction	Pumping sludge and air against a high static head require extra power
• Stainless steel reactor	Alkaline resistant, but not suitable for acidic reaction conditions	Costly material of construction
• Use air for both oxidation and mixing	No need for external mechanical agitation	Air "Channelling effect" may occur inside the reactor and causes inadequate mixing
• Neutral or alkaline medium	Caustic is added in high temperature-pressure Zimpro plant to reduce scaling in the equipment. Insolubilize the phosphates and the heavy metals in sludge	Scaling still occurs and equipment has to be washed with 5% nitric acid at scheduled intervals
• Phase separation outside the reactor	Both the gaseous phase and the liquid phase effluents are cooled in the same heat exchanger before separation	Both the gases and the oxidized sludge exit the reactor together; this tends to decrease the effective retention time of the sludge inside the reactor
• High temperature-pressure Zimpro unit operates at 525°F, (∿ 284°C) 1600-1750 psi, (∿11232-12066 kPa) pH adjusted to approx. 8.2 with caustic, retention time of sludge inside reactor is approx. 40-60 minutes	For high temperature-pressure oxidation, 65-75% organic reduction and 70-90% suspended solid reduction can be achieved. Reaction is self-sustaining	High temperature-pressure system, therefore high capital and operating cost
• Low temperature-pressure Zimpro Unit operates at 350°F, (~177°C), 400 psi, (~2758 kPa), 40-60 minutes of retention time	For low temperature-pressure sludge conditioning, 5-10% COD reduction and 17-31% suspended solid reduction. Because of lower temperature and pressure, this system has a lower capital and operating costs than the high temperature-pressure Zimpro Unit	The sludge is not destroyed but only conditioned for subsequent dewatering and incineration. External steam injection is required to keep the conditioning going
• High temperature-pressure Zimpro effluent is pumped into a nearby lagoon for settling of solids, supernatant liquor from the lagoon is recycled to secondary treatment plant	Power recovery from exit gases is possible, but encounter operational difficulties. Relatively simple process	Need a lagoon to dewater. Non-condensable gases are incinerated before discharged to atmosphere
• Low temperature-pressure Zimpro effluent is thickened and dewatered by vacuum filtration. The filter cake is either incinerated or land filled	The filter cake is sterile and may be suitable for soil conditioning. Incineration is self-sustaining and only a small volume of sterile, inert solids remains after incineration	The process is more complicated and involves more process steps than the high temperature-pressure Zimpro process

For a 50 tons (∿ 45 metric tons) dry solids per day high temperature-pressure Zimpro plant (Akron) operating at 50% capacity, the cost is estimated at \$70 per ton dry solids (∿ \$77 per metric ton dry solids).

For a 100 tons (∿ 91 metric tons) dry solids per day low temperature-pressure Zimpro plant (Kalamazoo) operating at 60% capacity, the cost is \$37 per ton dry solids (∿ \$41 per metric ton dry solids).

RECOMMENDATIONS

Based on the results of the feasibility study, the following recommendations are made:

- The present Ontario Research Foundation (ORF) evaluation of the Wetox performance is mainly based on the analysis of data obtained from three runs, all carried out at Barber-Colman's pilot plant. Therefore, in order to increase the confidence level of ORF's evaluation, a few Wetox experiments should be carried out independently, perhaps at ORF. The optimum sludge processing conditions as determined by Barber-Colman should be simulated using the Wetox semi-batch unit available at ORF. Various types of primary and secondary sludges obtained locally should be tried and samples from these experiments collected and analysed. Potential operational problem areas should be investigated. For example, contaminants in non-condensable gases exiting from the Wetox should be analysed to determine if the gases are required to be incinerated before discharging into the atmosphere. The disposal of the mixture of lime sludge and inert residual solids precipitated from the Wetox effluent should also be tried experimentally. From these experimental data, a more detailed cost analysis can be made and the performance results thus obtained should indicate closely the feasibility of using such a process for Canada-Ontario sludges.

  It has been suggested by Barber-Colman Co. that part or all of the Wetox effluent (after lime treatment) should be recycled to the denitrification stage of the sewage treatment plant. The 2000-5000 ppm low molecular weight organic acids contained in the recycled Wetox effluent may serve as excellent nutrient for the denitrifying bacteria in lieu of the methanol conventionally used for the purpose. Since the denitrifying step is becoming popular in wastewater treatment, such a cost saving possibility should be investigated in more detail.

- The present ORF evaluation also indicates that Wetox may have high potential for sludge disposal in small communities where land spreading is unsuitable. Accordingly, a feasibility study should be carried out to determine if Wetox is indeed more favourable technically and economically than other conventional sludge disposal processes under such circumstances. Preliminary experiments may be carried out to optimize the Wetox process for small scale sludge disposal.

- Low key efforts should be made to continuously monitor the progress of the Wetox demonstration plant to be built with the support of the United States Environmental Protection Agency. When the plant is in operation, data should be obtained and evaluated carefully. Such data will be essential for determining the plant scale Wetox performance.

1. INTRODUCTION

Large tonnages of sewage sludge produced from both the primary and secondary treatment processes present a difficult disposal problem. Conventional methods for sludge disposal include land spreading, heat treatment, wet oxidation, dewatering, incineration and landfill. Usually, more than one of the aforementioned treatment steps have to be employed in combination and the resulting overall process is complicated and costly. Depending on the characteristics of the sludge, the land disposal standard required by the local regulatory agencies as well as the availability of suitable land space near the treatment plants, the cost of the ultimate disposal of the sludge solids alone can amount to as much as 50% of the total cost of the entire sewage treatment plant (1).

With the critical shortages of land space in and near cities, the public pressure to cut the soaring cost of operating the sewage plants, as well as the imposition of more stringent pollution regulations, there is an urgent need to improve the efficiency of existing conventional methods for sludge disposal and at the same time to develop new, efficient lower-cost methods.

Recently, Barber-Colman Company announced the development of the Wetox process. This process, although still based on the principles of wet air oxidation, is different from the existing Zimpro process in both reactor design and performance. According to the published literature by the company, the Wetox process appears to offer several distinct economic as well as operational advantages over the Zimpro process. An investigation was carried out by the ORF to evaluate the feasibility of applying the Barber-Colman Wetox process for sewage sludge disposal. This report summarizes the findings in the feasibility study.

2. BACKGROUND INFORMATION ON SLUDGE DISPOSAL PROCESSES

Sewage sludge is a complex mixture of waste solids forming a gelatinous mass which is very difficult to dewater. The organic fraction of the sludge, largely of biological origin, consists of lipids, proteins and carbohydrates, all bound by physical-chemical forces in a predominantly water gel-like structure. The "bound water" content of sewage sludge is 90-98%, the higher value being associated with waste biological sludge from secondary treatment processes.

In most cases, the sludge is digested anaerobically to reduce its solid content by approximately one-third with the generation of a methane-rich, low-grade ($\sim$ 600-700 Btu/ft^3 or $\sim$ 22249-26081 kJ/m^3) fuel gas as a by-product. The gas generation is increasingly attractive economically in light of the anticipated sharp price increase in conventional hydrocarbon fuel. However, the digestion process is slow and requires extensive area to accomodate large tanks. It is also subject to interferences from toxic wastes. Moreover, the digested sludge is still voluminous, contains residual pathogens as well as high concentration of organic matters, and is just as difficult to dewater as the raw sludge. Alternatively, a smaller number of plants employ aerobic digestion for stabilization of their sludge. Of the 69 Ministry of the Environment plants in Ontario, 46 use anaerobic digestion and 10 plants, including Hagersville, a conventional activated sludge plant, employ aerobic digestion (2).

All these sludges, either raw or digested, must be ultimately disposed. There are many sludge disposal processes either now in use or still under development for such purpose. A complete detailed review of all these processes is beyond the scope of the present study. Nevertheless, brief evaluations of a selected few of the most common processes and the most well known new developments are presented separately in the following sections.

2.1 Conventional Processes Commonly Used for Sludge Disposal

The evaluation of the most common processes used for sludge disposal can best be summarized in the following Table 2. It is

TABLE 2. EVALUATION OF MOST COMMON CONVENTIONAL PROCESSES USED FOR SLUDGE DISPOSAL.

Process Description	Advantages	Disadvantages	Cost (in 1972)	Additional Remarks
- Land spreading of raw or digested sludge (3) - In a few plants, some concentration of sludge is performed via conventional settling tank and prior to land spreading; under these circumstances the cost of concentration is not differentiated from the total cost of disposal.	- Dewatering and solid disposal are accomplished in one operation - No recycling of supernatant liquor - Sludge can fertilize and condition the soil - Marginal land can be reclaimed and upgraded	- Mismanagement of sludge spreading inevitably leads to nuisance odours and polluted ground and runoff waters - Although there is no evidence that proper spreading of digested or stabilized sludges will cause disease to men or animals, disinfection may be needed when people come into contact with sludge - Effects of heavy metals leachout are still under study - Excessive land is required for the spreading, thus making it unattractive for treatment plants situated in large urban centres	- In Ontario, cost of spreading ranges between \$.70 to \$3. per cu yd with an average of \$1.40 per cu yd (~ \$1.80 per cu meter). Assuming a solid content of 5% in sludge, the cost is ~ \$33 per ton (~ \$36 per metric ton) dry solids (2) - In the U.S., cost ranges from \$5 (Franklin, Ohio) to \$62 (Chicago) per ton dry solids (~ \$6 to \$68 per metric ton) depending on whether the land for spreading is available next to the treatment plant or 200 miles (322 km) away. Most plants have the cost ranging between \$11 to \$30 per ton solids (~ \$12 to \$33 per metric ton) (3)	- Land spreading is very common in North America and in Europe - In Ontario, land spreading is mostly used for sludge disposal - In heavily populated areas in Europe, pathogens destruction may be required before the sludge can be spread. Either lime treatment or pasturization can be used. Additional cost of \$9-\$15 per ton (~ \$10-\$17 per metric ton) dry solids is estimated
- Dewatering on sand beds (4) with subsequent land disposal of the dried sludge	- Simple to operate - Solids can be dewatered down to 50% moisture content	- Excessive land requirement thus making it unattractive to treatment plants situated in large urban centres - Operation cycles vary depending on local climatic conditions and the season	- Estimated to be varying between \$20-\$39 per ton (~ \$22-\$43 per metric ton) of dry solids depending on the cost of land - Cost of the ultimate spreading of the dried sludge (50% moisture) is extra	- Approximately 70% of the treatment plants in the U.S. employed sand dry bed for sludge dewatering in 1957 - The dried sludge can be used as a compost fertilizer or as top soil for farm use - This method is expected to be popular with small and medium size plants in the U.S.
- Dewatering followed by land spreading, or followed by incineration-landfill or followed by heat drying - Dewatering methods include vacuum filtration (5), pressure filtration (6), and centrifugation (7) - Incineration can be achieved most commonly by either multiple hearth or fluidized bed incinerators	- Require a minimum land space for the operation. Therefore the process is suitable for treatment plants situated in large urban centres where land is expensive - In the case of dewatering followed by land spreading the dewatered sludge can now be transported to farmland at a lesser cost than the raw sludge because of the ~ 75-50% as compared to the original 95% moisture content - In the case of dewatering followed by incineration, a large volume of sludge is reduced to only a very small volume of sterile inert solids. Incineration is almost self sustaining; but sometimes a small amount of fuel addition may be required - The solids obtained from dewatering followed by heat drying may be suitable as soil conditioner	- Require high capital investment - Prior to dewatering, chemical conditioning is usually required. The chemicals may cause difficulties to the subsequent treatment steps - The dewatering step may be odorous and difficult to operate; filter clogging is not uncommon; substantial quantities of solids may be recirculated in the supernatant liquor - In the incineration, inert solids, though in small amount still needed to be landfilled	- Total cost for either vacuum filtration or centrifugation operation is estimated at ~ \$14 per ton (~ \$15 per metric ton) dry solids - Dewatering followed by landfill costs ~ \$26 per ton (~ \$29 per metric ton) dry solids (5) - Dewatering followed by incineration costs ~ \$30 per ton (~ \$33 per metric ton) dry solids (8) - Dewatering followed by heat drying can go higher than \$40 per ton (~ \$44 per metric ton) dry solids (3). However, the solids may be sold as soil conditioner	- Out of the 69 Ministry of the Environment sewage plants in Ontario, only three plants (Port Dover, Sault Ste. Marie and Preston) dewater raw sludge by vacuum filtration. A centrifuge is used at Simcoe to dewater sludge
- Sludge conditioning by either heat treatment or low temperature-pressure wet air oxidation. The conditioned sludge is then dewatered and incinerated. The ash is landfilled.	- Require a minimum of land space for operation. Therefore the process is suitable for treatment plants situated near large urban centres where land is expensive - No chemical conditioning is required - Relatively odour-free operation - Incineration is self-sustaining, and only a small volume of sterile, inert solids remains after incineration	- Require high capital investment - In the dewatering step, a substantial quantity of fine solids and BOD in the filtrate may be recirculated back to the secondary treatment plant	- Total cost to operate a large size wet air oxidation (100 dry tons or ~ 91 dry metric tons per day) plant is ~ \$32 per ton or ~ \$35 per metric ton (8) - For heat treatment plants in England, cost of \$35 per ton (~ \$39 per metric ton) dry solids was reported (9)	- In the U.S. both Zurn Industries Inc. and Envirotech Systems Inc. manufacture systems based on the Porteous process. Only Zimpro Co. manufactures wet air oxidation system commercially - The first Canadian Zimpro plant is in Lakeview Sewage Plant in Mississauga scheduled to operate in late 1974

interesting to note that all these processes have a total operating cost roughly at around \$30 per ton ($\sim$ \$33 per metric ton) dry solids.

2.2 New Methods Developed For Sludge Disposal

There are numerous new sludge disposal methods either under development or at the stage of commercialization. Most of the new methods emphasize producing re-usable by-products rather than straight destruction of organics. Examples of these methods include acid hydrolysis, biological fractionation, pyrolysis, freezing, the Scheel process and the worm process. Four of these methods are particularly interesting and they are further elaborated individually in the following:

2.2.1 Pyrolysis

Pyrolysis may be defined as the destructive distillation of organic materials in the absence of oxygen. The resulting useful products are a combination of combustible gases, tars, oils and solid residues. The distribution of these products is dependent on the process operating conditions as well as the sludge characteristics.

In late 1973, the Metropolitan Sewer Board of the Twin Cities serving Minneapolis - St. Paul and additional nearby municipalities, awarded a \$10 million contract for the first stage of a pyrolysis plant which will convert both sewage sludge and solid waste refuse and produce the usable by-products (10).

2.2.2 Freezing (Suitable for Areas Which Have Long Cold Winters)

This technique of sludge disposal is being applied by the City of Winnipeg's sanitary engineers. The digested sludge is pumped into drying beds and allowed to settle. The high solids bottom layer is then frozen by the winter cold.

The frozen sludge is bulldozed out, loaded on trucks and hauled to nearby farmlands where it is used as fertilizer. The operating costs are only \$0.95 per ton ($\sim$ \$1.05 per metric ton) dry sludge - by far cheaper than all competitive processes (11).

2.2.3 The Scheel Process

H.P. Scheel (12) patented a process based on mixing dewatered

sludge with sulphuric acid and magnesium oxide. Heat from the resulting exothermic reaction is sufficient to raise the mixture above $200^{o}F$ ($\sim 93^{o}C$), thereby sterilizing and deodourizing the sludge. In addition, the two chemicals' reaction product-magnesium sulphate-contains seven molecules of bound water. This reduces the amount of subsequent drying needed to turn the reactor effluent into a salable product. Both magnesium and sulphur are essential plant nutrients thus making the product suitable as lawn fertilizer and soil conditioner.

2.2.4 The Worm Process

A $1000 grant was funded in 1972 by the Waste Management Branch of the Ontario Ministry of the Environment (13) to investigate the effectiveness of stabilizing sludge utilizing red worms as mixing agents. An almost perfect soil can be produced and the well fed worms can be "harvested" as an income supplement, provided the worm and the soil can be separated easily.

3. DESCRIPTION OF THE WET AIR OXIDATION PROCESS

In this section, both the Barber-Colman Wetox process and the Zimpro process will be described in some detail. Since both processes are based on the principle of wet air oxidation, it seems appropriate to fully explain the general mechanism of wet air oxidation first before going into individual detailed descriptions of these specific processes.

3.1 Comparison Between Wet Air Oxidation And Dry Incineration

Wet air oxidation is a chemical reaction occurring in a liquid medium between oxygen and suspended or dissolved combustible matter. Thermodynamically, such reactions are analogous to those occurring in simple burning (direct combustion), i.e. the amount of heat liberated and the end products formed are the same as when oxygen gas (usually added as air) reacts directly with organic matter, as in the incineration of trash, to form CO_2 and H_2O. Kinetically, however, wet air oxidation differs significantly. It is more difficult to initiate and sustain than direct combustion unless conducted at temperatures above the normal boiling point of water and most other common liquids. Wet air oxidation, therefore, is conducted in an autoclave, a pressurized chamber wherein a liquid and its vapour are confined with oxygen gas under conditions (temperatures, oxygen partial pressures and concentration of absorbed oxygen) more favourable than those obtainable under normal ambient conditions. Even in an autoclave, wet air oxidation occurs sluggishly and is liable to be incomplete unless provisions are taken to assure effective transfer of oxygen gas to the combustible matter. In addition to increases in temperature and oxygen partial pressure, the rate of oxygen transfer is significantly increased by effective agitation or mixing.

The process is a convenient way to destroy organic waste contained in water without evaporating or otherwise removing the water from the organic matter as required before incineration. For the same reason, the reduction of air pollution is effected in wet oxidation because the products of combustion are automatically and thoroughly scrubbed. In wet air oxidation, usually less than one-third as much

heat is expended in preparing the organic matter for oxidation in the case of evaporation/incineration.

In both processes, the actual combustion of the organic compounds is an exothermic reaction: therefore, provided there is enough organic matter present, once oxidation is initiated, it can proceed autogenously. Combustion is self-sustaining and in fact, the excess heat from large wet air oxidation systems has been used to generate power and electricity. Table 3 summarizes the analogies between incineration and wet oxidation.

TABLE 3. COMPARISON BETWEEN DRY INCINERATION AND WET AIR OXIDATION.

DRY	WET
- Low-moisture Fuel	- Watered Fuel
- Low-pressure Air (slightly above atmospheric pressure)	- High-pressure Air (usually 400-2000 psi or 2758-13790 kPa)
- High Temperature Ignition (usually 1400-1600^{o}F or 760-871^{o}C)	- Low Temperature Ignition (usually 350-550^{o}F or 177-288^{o}C)
- Oxidation	- Oxidation
- Heat Combustion	- Heat Combustion
- Auto-oxidation	- Auto-oxidation
- Air Pollution	- No Ait Pollution
- Need Incineration	- Need Wet Oxidation Reactor
- Heat Recovery	- Heat Recovery with Power or Electricity Generation

3.2 Technical Discussion of Wet Air Oxidation

In the wet air oxidation of waste materials, both dissolved and suspended in water, such as sewage sludge, there are at least three basic types of chemical reactions involved. These competing reactions--heterogeneous (solid surface) oxidation, hydrolysis and liquid-phase oxidation--all commence simultaneously as soon as the aqueous slurry is exposed to elevated temperatures and pressures. Initially, the destruction of organic waste is predominantly the result of heterogeneous oxidation on

the solid surface of combustible matter: i.e. the direct contact and ensuing reaction between absorbed oxygen gas and organic solids. However, these solids are mostly cellular clusters, flocs and gels loosely bonded into macromolecules, often by water. At elevated temperature, they are also quickly reduced to colloids (and solubilized) by hydrolysis; i.e they are attacked by internally bonded water and by the water that surrounds them. Soon, there is no longer sufficient surface for a heterogeneous reaction to take place. Hydrolysis generally splits the organic polymers into smaller units but does not destroy them. The only remaining path for ultimate destruction of organic matter is the liquid phase oxidation. Disregarding these complex reaction steps and considering the wet air oxidation from an overall point of view, the reaction apparently proceeds to produce lower molecular weight oxidized compounds typically from high molecular weight reactants (14) (15). Part of the reactants are oxidized all the way to CO_2 and H_2O, while remaining part is oxidized to low molecular acids such as acetic. Acetic acid oxidizes only at a very slow rate and therefore it is not unexpected that some of it will remain as one of the end products.

There are three physical parameters governing the overall rate and extent of the oxidation reaction. They are temperature, pressure and retention time. In addition, the process equipment must be designed with adequate mixing to supply oxygen from the gas phase into the slurry at a rate equal to or faster than the rate of utilization. According to the rocking autoclave experiments performed by Zimpro Co. (15) (16), the rate and the extent of oxidation achieved is primarily determined by the maximum temperature reached in the reactor as indicated in Figure 1 for sewage sludge. At low temperatures, long periods of retention time are required to reach equilibrium and this equilibrium is at a lower level of oxidation. At temperatures of $\sim 480^{o}F$ ($\sim 249^{o}C$) and above, equilibrium levels are attained in a very short time. The system pressure, on the other hand, is indirectly controlled by the system temperature. Enough pressure must be applied to the autoclave such that the effluent air will not carry away all the liquid phase and stop the reaction.

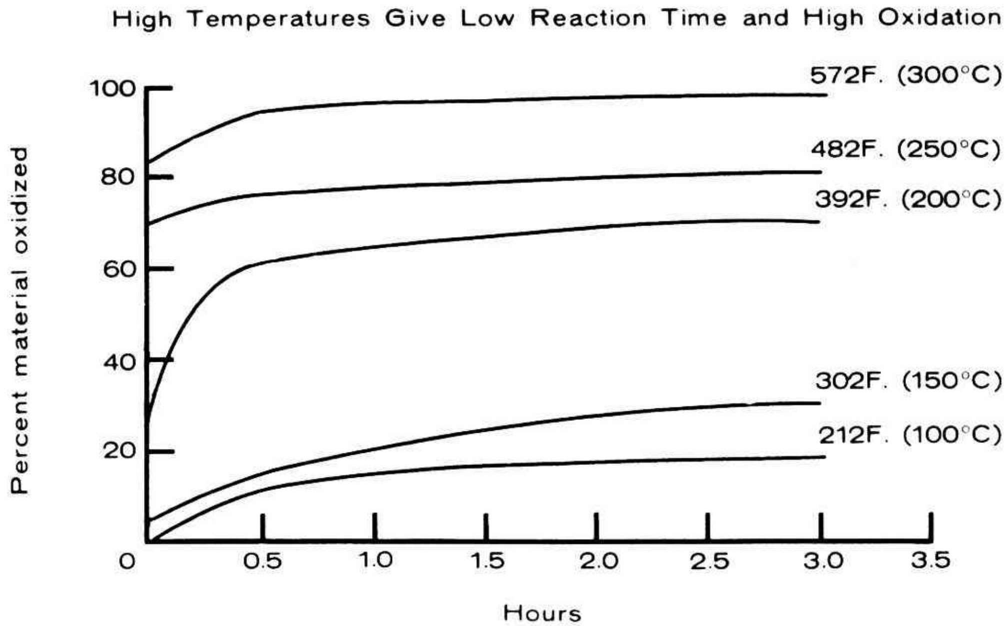


Figure 1.

Laboratory Scale Sewage Sludge Oxidation Performed by Zimpro Co.

Without going into further detailed descriptions, characteristics of the overall wet air oxidation are summarized as follows:

- Reaction produces CO_2 and H_2O, plus some low molecular weight acids e.g. acetic.
- Reaction has an initial extremely rapid rate followed somewhat abruptly by a much lower rate (Figure 1). Initial rapid reactions (Stage 1 reaction) are probably due to a combination of solid phase oxidation and liquid phase oxidation of the easily oxidizable organics. The much slower rate (Stage 2 reaction) is probably due to liquid phase oxidation of the low molecular weight acids as well as the oxidation-resistant materials originally present in the sludge.
- Reaction reaches a different ultimate equilibrium level at different temperatures (Figure 1). The higher level of organic destruction to CO_2 is obtained with higher temperature. Only at temperatures of $450^{\circ}F$ and higher can a considerable amount of COD (say 80% of initial) be removed (Figure 2) (17).
- Adequate mixing to supply oxygen from gas phase into the slurry for reaction is essential.

Amount of C.O.D. Removal is Mainly Function of Reaction Temperature

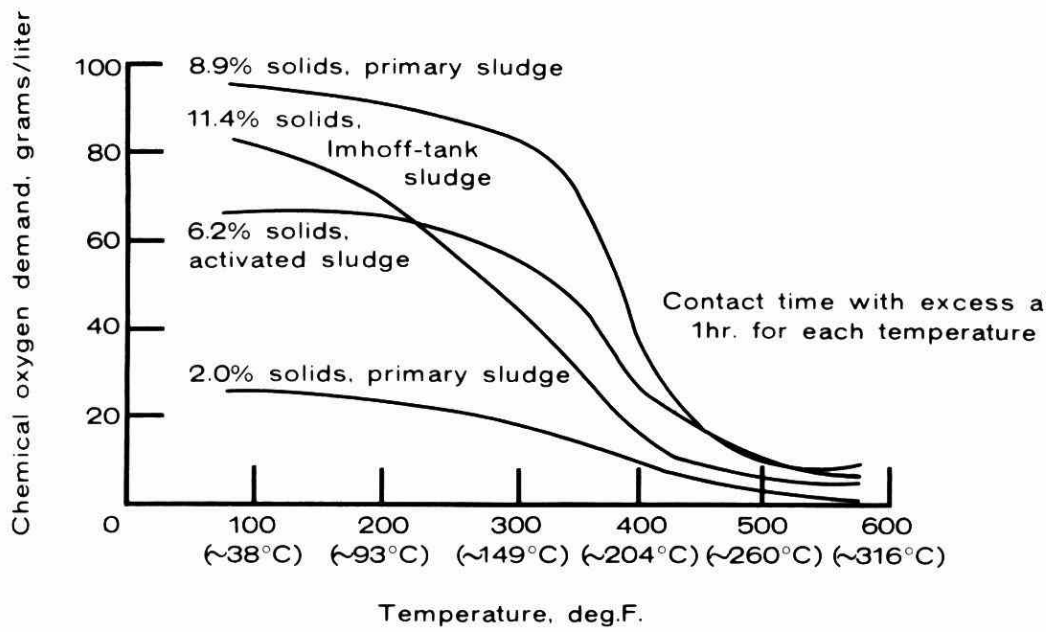


Figure 2.

Laboratory Scale Sewage Sludge Oxidation Experiments Performed By Zimpro Co.

- Oxygen pressure has no effect on the rate or the extent of organic destruction providing stoichiometric amount of oxygen is supplied.
- Optimum retention time of the sludge is ∿ 1 hour.
- Organic nitrogen compounds are converted to ammonia, and sulphur to sulphate (18).

3.2.1 <u>Wet air oxidation in acidic medium</u>

Barber-Colman Company has conducted extensive experimental investigation aimed at finding means to improve the wet air oxidation efficiency of the sewage sludge. By using vigorous mixing in a stirred autoclave as well as a small amount of acid addition, which are the ingredients of the Wetox process, the efficiency of oxidation is enhanced. Figure 3 illustrates a typical comparison of laboratory scale data between wet air oxidation under acidic medium (Wetox) and under neutral medium (Zimpro). The experiments in both cases were performed with municipal sludge. The "neutral medium" data were from rocking autoclave experiments performed by Zimpro (Figure 3) and the "acidic medium" data

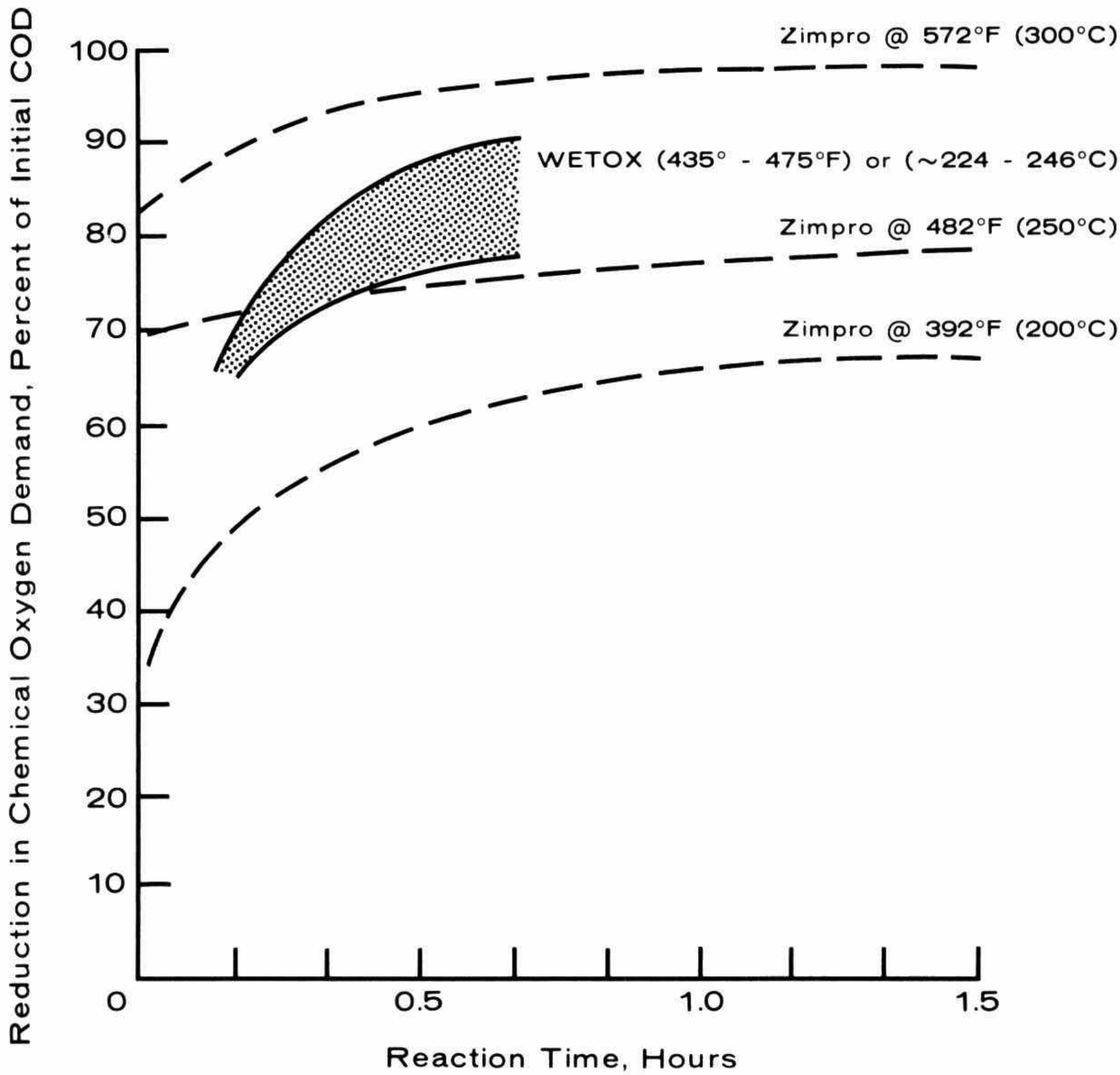


Figure 3

Comparison Of Laboratory Scale Of Wetox And Zimpro Processes For Wet Oxidation Of Sewage Sludge

were from Barber-Colman laboratory tests conducted on raw primary sewage sludge from the city of Laguna Beach, municipal sewage treatment plant in California.

It is noted that the oxidation efficiencies obtained by laboratory experiments are, on the average, slightly higher than those obtained by pilot scale or plant scale operations. This is probably because the process parameters (e.g. batch-wise mixing etc.) are controlled under more ideal conditions for reaction.

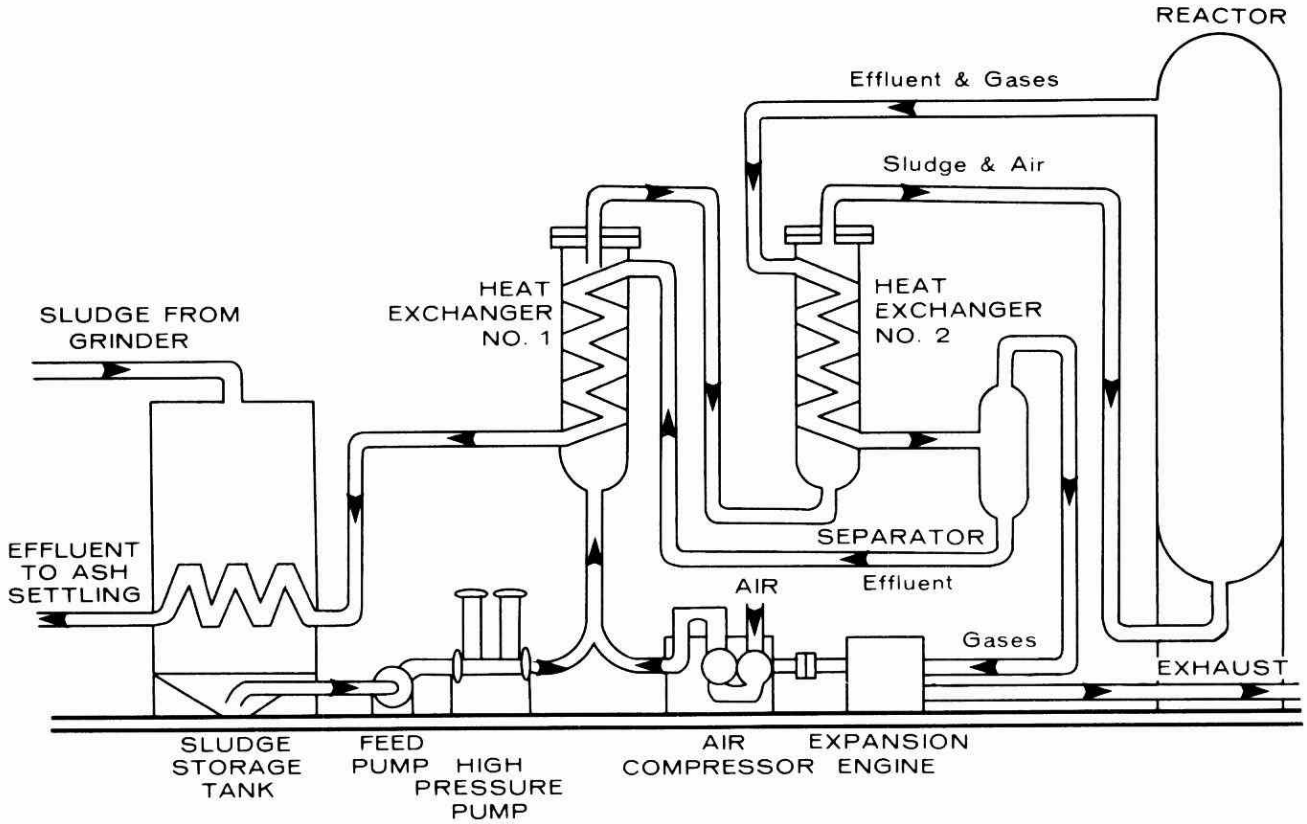
3.3 Zimpro Process

As discussed in the previous section, the laboratory data from rocking autoclave experiments indicate that the controlling parameter in wet air oxidation is temperature (apart from adequate mixing). Accordingly, Zimpro plants are designed individually, each to operate at a particular temperature level. The choice of the operating temperature depends on the desired degree of organics destruction and on the characteristics of the sludge to be oxidized. In general, Zimpro plants can be classified in two categories - the high temperature-pressure plants are used for sludge oxidation while the low temperature-pressure plants are used for sludge conditioning.

3.3.1 Zimpro plants used for sludge oxidation

Plants in this category have operating conditions usually in the range of 480-525^{o}F ($\sim$ 249-274^{o}C) and 1200-1800 psi ($\sim$ 8274-12411 kPa). Under these conditions, 65-75% COD reduction and 70-90% suspended solids reduction can be achieved. Using normal sludge of 3-6% solids content, the heat liberated from oxidation is enough to sustain the reaction without any external heat addition. The operation of this type of plant is best summarized in the Zimpro Technical Bulletin (1964) as reproduced in Figure 4. For large size plants operating at 1600-1800 psi ($\sim$ 11032-12411 kPa) such as those in Chicago and Akron, power and electricity recovery from effluent gases exiting the reactors is attempted although with technical difficulties. For small size plants operating at 1200 psi ($\sim$ 8274 kPa) such as those in Hockford Works (England) (9) and Wheeling (19), no power recovery from the exit gases

FLOW DIAGRAM OF ZIMPRO WET AIR OXIDATION UNIT



OPERATION OF THE ZIMPRO WET AIR OXIDATION UNIT

EQUIPMENT—The major pieces of equipment required for continuous oxidation (burning) are: a reactor, an air compressor, heat exchangers, sludge pump, control valves, separators, and an expansion engine, or turbine, if applicable, to recover energy in the gases and steam produced.

OPERATION—In the Process, the waste material and air are introduced in proportionate quantities into the system and brought to the necessary operating pressure by their respective pumps. Operating pressures may be from 150 to 3000 lbs. per sq. in. depending on the size of the plant and the degree of oxidation desired. The operation is maintained at the required pressure by an automatic pressure control valve.

For startup, required heat is obtained from an outside steam source—usually a small flash boiler. Once the Process is started, no external heat is needed to maintain "burning." The sludge and air are then heated to the oxidation temperature by specially designed heat exchangers (No. 1 and No. 2 on Flow Diagram). In a typical sewage sludge oxidation, the mixture enters the reactor at about 400°F. At this temperature oxidation will proceed at a predetermined rate. Normally, reactor temperatures reach appoximately 500°F. but may, if required, go to 705°F., the critical temperature of water. Above this point, water cannot be maintained in the liquid phase. Contrary to ordinary burning, liquid water must be present in Wet Air Oxidation.

Contents from the reactor now move forward to a heat exchanger (No. 2 on Flow Diagram) where some excess heat is removed to preheat incoming sludge. Next the contents may be separated in a gas-liquid separator. The water carrying the ash then heats the incoming sludge in another heat exchanger (No. 1 on Flow Diagram) and is finally cooled by giving up heat to cold sludge in the storage tank.

The ash can be separated from the liquid by settling in a lagoon or settling tank. The ash makes excellent fill material, is biologically stable and free of obnoxious odors.

The residual water may be returned to the main sewage flow. This oxidized liquid is considerably less than 1% of the total sewage flow.

The gases, mainly CO_2, nitrogen and water vapor may be expanded to run a directly coupled air compressor or a generator for electric power production. Where there is sufficient "combustible" material and the unit is large enough, the Process, once started, requires no external power.

Figure 4. High Temperature-Pressure Zimpro Plant Operation.

is made, and the effluent gas-liquid mixture from the reactor is cooled through heat exchange with in-coming sludge before separation.

Because of the high temperature and pressure requirements, capital cost of this type of plant is high. As an example, the 200 tons/day ($\sim$ 181 metric tons/day) plant in Chicago cost $20 million in 1961. Over the years, with accumulated manufacturing experience as well as streamlined production, Zimpro has been able to reduce the cost gradually. Nevertheless, the more recent 50 tons/day ($\sim$ 45 metric tons/day) Akron plant still cost $2.75 million in 1970.

The vertical configuration of the reactor and the heat exchangers in the Zimpro plants is intended to be compact and occupy a minimum of plant space. Inside the reactor and under ideal operating conditions, the sludge and air are mixed and forced to flow up. The large volume of air travelling upward at a speed faster than the sludge should create turbulent mixing without the help of external mechanical agitation. The larger the volume of air input, the more vigorous the mixing, but there is more heat loss (because more water vapour is carried away from the system) and higher operating cost (since transporting air and sludge under high pressure is the principal cost in wet air oxidation). Thus the Zimpro plants rarely use a great deal of air in excess over the stoichiometric amount. In addition, "channelling effect" may occur to some extent in a vertical reactor and reduce the effective mixing between air and sludge. In the present reactor design, both the gases and the oxidized sludge exit from the reactor together. This design tends to decrease the effective retention time of the sludge, because for maximum oxidation efficiency, the sludge should remain inside the reactor longer than the air.

The vertical configuration of the reactor and the heat exchangers (30 - 80 feet or $\sim$ 9 - 24 meters tall) also causes difficulties in installation and maintenance. In addition, caustic is added to the sludge to maintain alkalinity (pH is $\sim$ 8 to 8.2) to minimize scaling in the reactor and heat exchangers. Despite the caustic addition, scaling still occurs, although at a slow rate, thus requiring plant shut downs and acid wash to de-scale the equipment at intervals.

In summary, it appears that high temperature-pressure plants have high capital equipment as well as operating costs, thus making them less competitive with other conventional processes for sludge disposal. A personal visit to the Akron Zimpro plant verifies the aforementioned discussions. The summary of the visit is included in Appendix I.

3.3.2 Zimpro plants used for sludge conditioning

In order to reduce cost and circumvent the operational difficulties encountered in the high pressure oxidation plants, the process has been modified and the design of the more recent plant version leans toward lower temperature and pressure operation with progressively less solids reduction and a product slurry containing higher COD value. The basic process flowsheet is similar to that of the high temperature, pressure plant but modified to operate without power recovery from the effluent gases as shown in Figure 5. The configuration of major equipment remains unchanged.

There are many low temperature-pressure Zimpro plants currently in the U.S. A well-known example can be found in Kalamazoo, Michigan. The plant is operated at $350^{o}F$ ($\sim$ $177^{o}C$) and 400 psi ($\sim$ 2758 kPa). Under these conditions, a low degree of oxidation in the sludge occurs. COD reduction of 5-10% as well as suspended solids reduction of 17-31% are achieved. Not enough heat is derived from the oxidation to sustain the reaction and additional heat has to be supplied constantly to the system by steam injection. After the thermal conditioning, the sludge can be gravity thickened to $\sim$ 10% solids easily. The filtrability of the solids also improves and vacuum filtration of the thickened sludge can give a sludge cake containing 42% solids without any addition of chemicals. On the other hand, the residual liquor after filtration has a high COD value and is recycled back to the secondary treatment plant. The pH in the system is generally about 7. In order to combat the scaling problem, the critical equipment pieces (e.g. reactor and heat exchangers) are washed with 5% nitric acid at intervals. Consequently, the material of construction for the equipment is stainless steel. Nevertheless, the capital cost for the 100 dry tons/day ($\sim$ 91 metric tons/ day) Kalamazoo plant is considerably less than the high temperature-

1 Sludge is ground and pumped to about 300 psig reactor pressure.

2 Compressed air is introduced into the sludge and the mixture is brought to an operating temperature above 350°F by heat exchange and direct steam injection.

3 The heated conditioned sludge is cooled by heat exchange with the incoming sludge.

4 Gases are separated and released through a catalytic afterburner or equivalent odor control device.

5 Conditioned sludge is concentrated by settling and dewatered by filter, centrifuge or on drying beds.

6 Liquor, readily biodegradeable, flows to secondary plant or to separate treatment unit. Short reaction time assures minimum color and BOD.

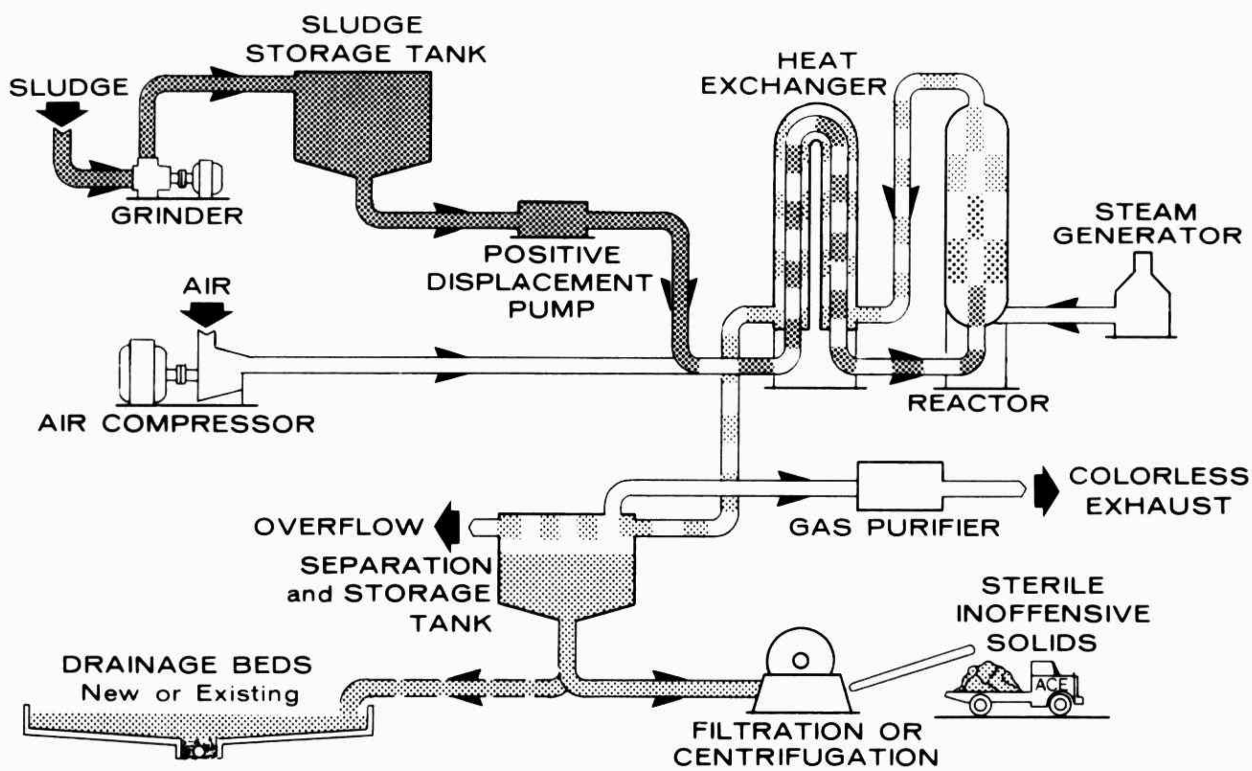


FIGURE 5

Flow Diagram of Low Temperature-Pressure Zimpro Plant as Reproduced from Zimpro Technical Bulletin #2130

pressure plant of equivalent capacity. The Kalamazoo Zimpro plant cost \$2.2 million in 1969.

After oxidation, the distribution of the phosphates as well as the heavy metals between the liquor-ash phases is still largely unknown and under investigation. Some preliminary experimental evidence tends to indicate that a large portion of the phosphates and heavy metals may stay bound in the ash.

The first Zimpro plant in Canada for sludge disposal is scheduled to be installed in late 1974 at the Lakeview WPCP in Mississauga by the Ontario Ministry of the Environment. The Lakeview Plant closely replicates the Kalamazoo Plant in size and operation with some extra accessory equipment being added at a somewhat higher cost.

In summary, the low temperature-pressure Zimpro unit is used as a sludge conditioner. Apart from the usual maintenance problems, these Zimpro installations have been generally operating within design criteria. A personal visit to the Kalamazoo Plant confirmed the satisfaction of the operating personnel with the Zimpro plant performance. The summary of the plant visit is presented in Appendix I. Because of the low COD oxidation as well as solids reduction, the treated sludge has to be concentrated, dewatered and either incinerated or landfilled. Even with all these post treatment steps included, the total disposal cost is ~ \$32/ton (or \$35/metric ton) dry sludge, and is competitive with other conventional sludge disposal processes, particularly in large urban areas.

3.4 Barber-Colman Wetox Process

By adapting the metallurgical technology and equipment used for pressure oxidation and acid leaching of sulphide ores to waste treatment, Barber-Colman Company has developed the Wetox process. The Wetox, although still basically a wet oxidation process, is different from the other existing wet oxidation processes, such as the Zimmermann process, in both reactor design and performance. The essential features of the Wetox process as described in the available technical bulletins (20) (21) published by Barber-Colman Company are presented in the following sections.

3.4.1 The Wetox process description

In the Wetox process, oxidation of liquid waste is carried out continuously at 450^{o}F and 600 psi ($\sim$ 232^{o}C and 4137 kPa) in acidic medium in a horizontal autoclave containing 4-6 compartments with individual stirring in each compartment. The process flowsheet is shown in Figure 6. Macerated sludge is pumped through a vapour phase as well as a liquid phase tube-in-tube heat exchanger and into the front end of the reactor, mixed with compressed air, and reacted in the first compartment, from which it overflows to the following compartment, consecutively undergoing more nearly complete oxidation in each compartment. Due to the presence of acid as well as adequate stirring to enable a high rate of oxygen transfer into slurry, destruction of organic matter is rapid and close to completion. Some inorganics, particularly sulphur compounds will be converted to sulphates. In the final compartment, liquid and vapour phases are separated and conducted separately to heat exchangers for thermal energy exchange with the in-coming sludge. Products resulting from the oxidation are automatically and thoroughly scrubbed, thus minimizing air pollution. Once the oxidation is started, large amounts of heat are usually generated which are not only sufficient to maintain a self-sustaining reaction, but also to provide excess heat for energy recovery if so desired. After cooling, the vapour phase is let down to atmospheric pressure as is the liquid phase. At this point, a variety of post-treatment steps may be used to further purify the effluents. In the flow sheet (Figure 6), a lime treatment step package (i.e. Wetox plus lime treatment) is marketed under the trade mark of "Puretec System" by Barber-Colman.

The choice of titanium (or acid brick lining for large reactors) as material of construction eliminates the corrosion problems. Since the reaction is carried out in an acid medium, scaling is minimized. The horizontal configuration of the autoclave also facilitates the maintenance and repair.

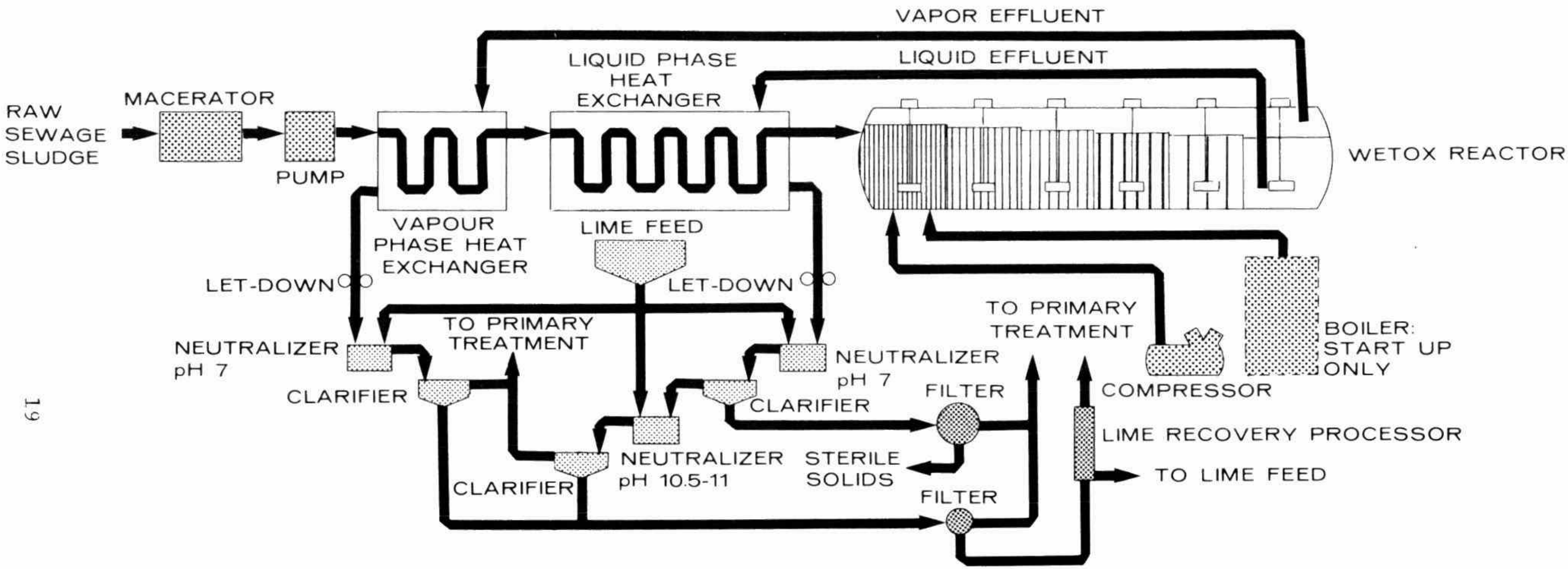


Figure 6.

Process Flowsheet of the Wetox Unit. A Lime Treatment System is Added on to Further Purify the Wetox Effluents. The Combined System (Wetox Plus Lime Treatment) is Registered Under the Trade Name of Puretec System.

3.4.2 The Wetox reactor sizes

Barber-Colman Co. currently markets a range of standard size Puretec Systems for disposal of sludge as well as other industrial waste. Table 4 shows the standard sizes of the continuous operation Wetox reactors.

TABLE 4. WETOX REACTOR SIZES.

Reactor Model	Number of Agitators	Reactor Diameter		Flow Per Hour*		Dry Tons Per Day**	
		Inches	mm	Gallons	Liters	English	Metric
4-10	4	10	254	20	129	0.1	0.09
6-12	6	12	304	200	1290	1.0	0.9
6-54	6	54	1372	3,000	19356	16.0	14.5
6-72	6	72	1829	6,000	38712	32.0	29.0

* 30 Minute Retention Time. ** 6% Dry Solids.

The conceptual view of the 32 dry tons (~ 29 metric tons) per day (Model 6-72) Wetox plant is shown in Figure 7. Except for Reactor Model 4-10, which is a pilot-plant scale unit, no commercial size plant based on the Wetox process has yet been built for sludge disposal (although commercial metallurgical plants using similar equipment for pressurized acid leaching of ores have been in existence for years). Autoclaves capable of processing sludge up to 16 dry tons (~ 14.5 metric tons)/day (Model 6-54) have been built but not yet put into operation. In addition, a special Wetox unit capable of processing 0.8 tons (~ 0.7 metric tons) dry solids/day was constructed and operated under a U.S. Navy contract to study the disposal of old explosives, film, sewage and solid wastes. The unit is shown in Figure 8.

For small volume sludge processing, semi-batch Puretec Systems may be advantageous. The flowsheet together with the conceptual view of a plant scale semi-batch system is shown in Figure 9. The operation is briefly described in the following:

- The sludge to be processed is loaded directly into the first reactor.
- A boiler is used to pre-heat the reactor and once oxidation begins, the heat of reaction is sufficient to maintain reaction.

1 - Compressor
2 - Accumulator
3 - Wetox Reactor
4 - Heat Exchanger
5 - High Pressure Pump
6 - Reagent Feeder (Optional)
7 - Vapour/Liquid Let-Down System
8 - Scrubber (Optional)
9 - Catalytic Oxidizer (Optional)
10 - Scrubber pH Control (Optional)
11 - Catalyst Recovery (Optional)

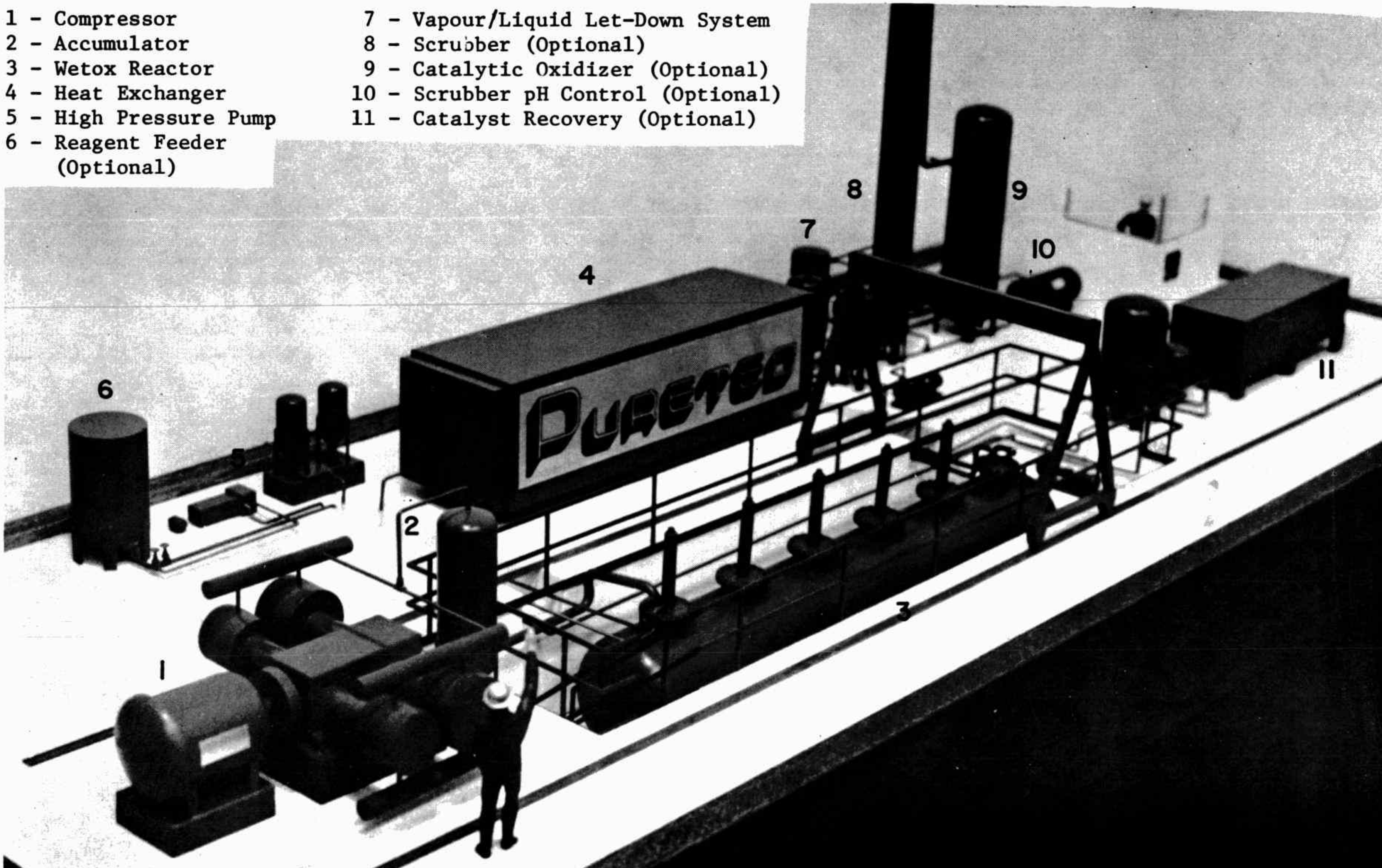


FIGURE 7. CONCEPTUAL VIEW OF THE 32 DRY TONS (~ 29 METRIC TONS) PER DAY WETOX PLANT (MODEL 6-72).

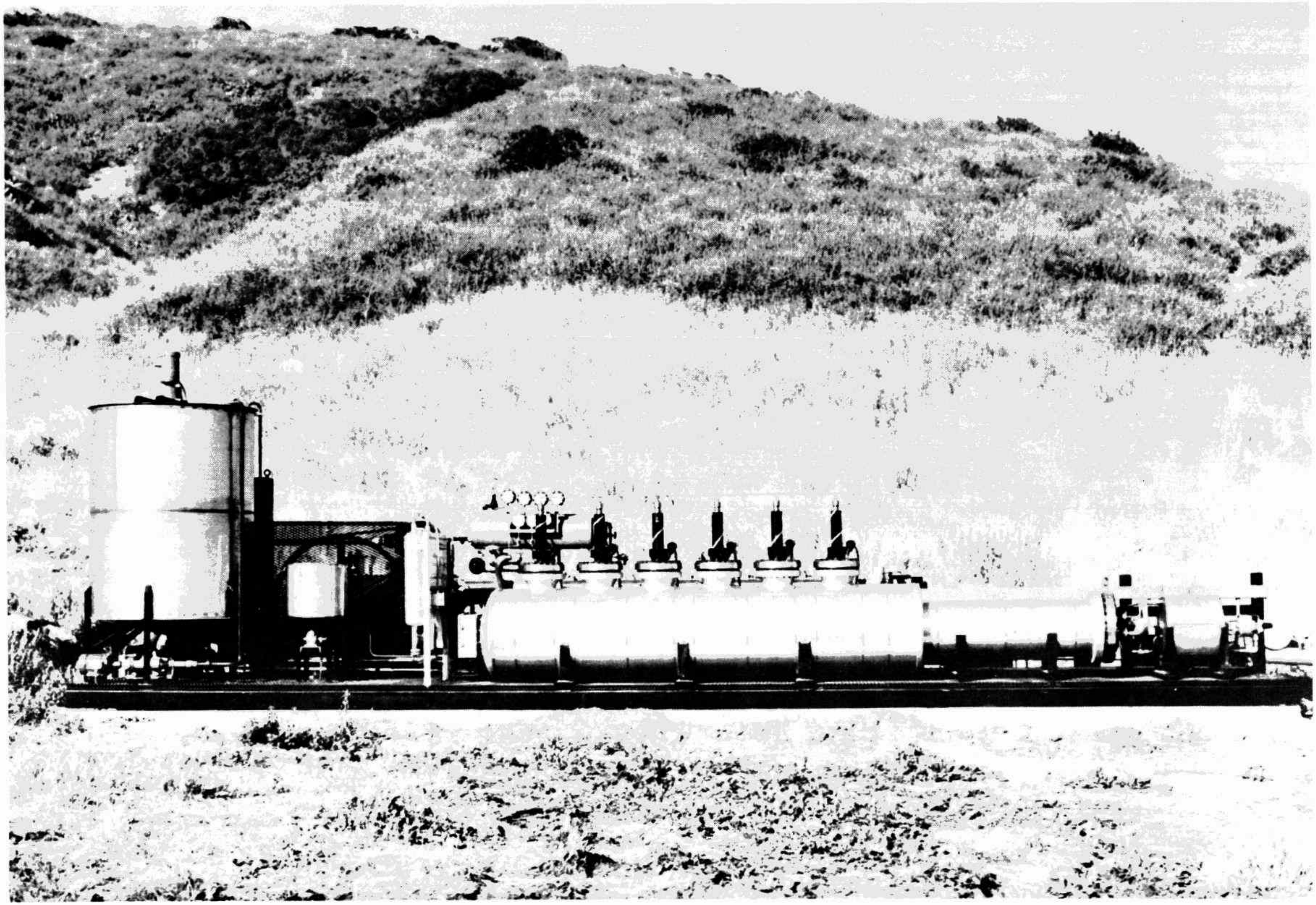


FIGURE 8. 0.8 TON (~ 0.7 METRIC TON) PER DAY WETOX UNIT FOR THE UNITED STATES NAVY.

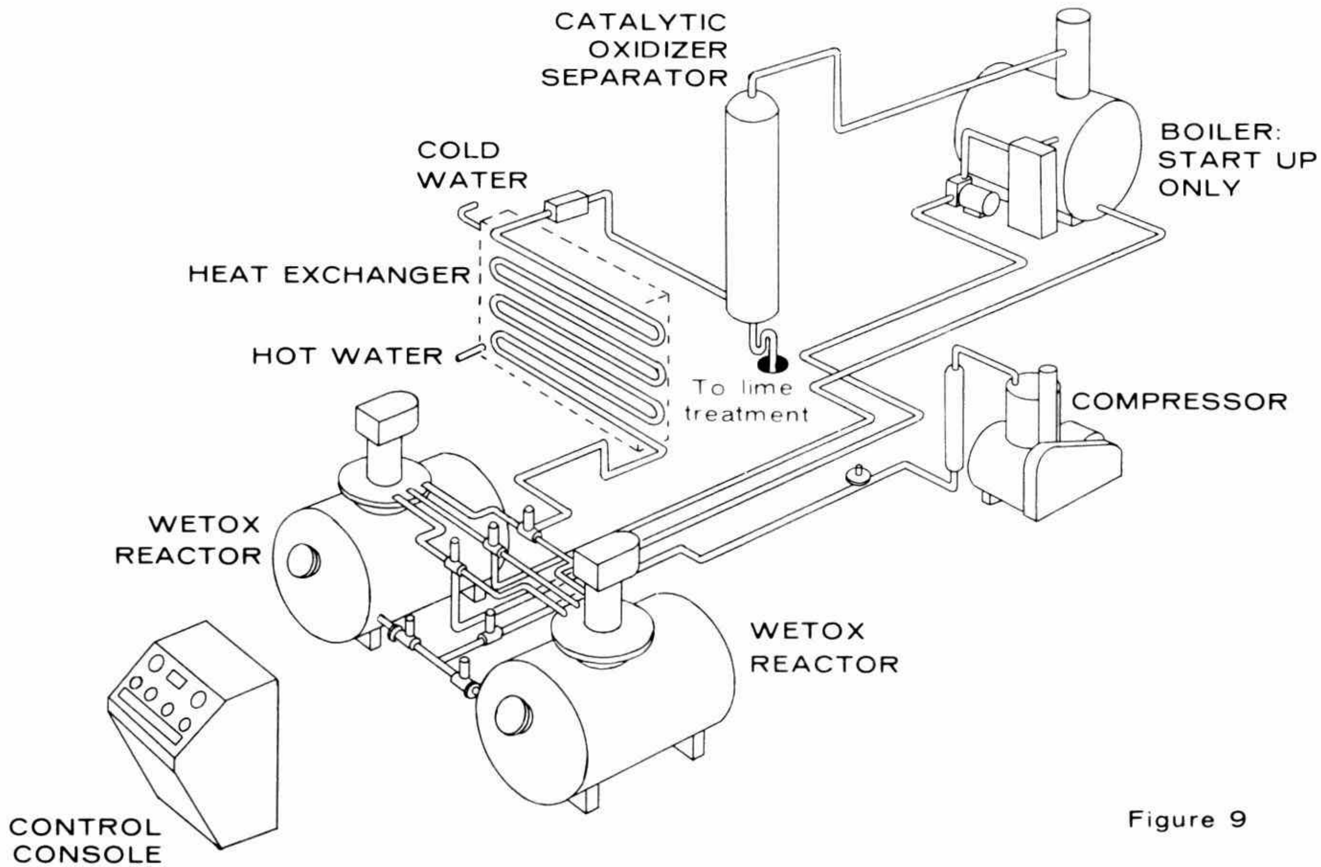


Figure 9

Semi Batch System

- Pressure is increased to 600 psi ($\sim$ 4137 kPa) by compressed air which serves as the oxidizing gas.
- The material is continuously agitated to insure complete reaction.
- Effluent is conducted from the reactor to heat exchange with the cold sludge in the second reactor (or to heat exchange with cold water).
- The cooled liquid effluent is further purified by lime-treatment while the non-condensables are scrubbed by a catalytic oxidizer before discharge.
- The heated sludge in the second reactor is now ready for oxidation by compressed air.

A 3-gallon capacity (each reactor) semi-batch unit is currently in operation at the Barber-Colman Company.

3.4.3 Wetox performance

As mentioned before, there are, at present, no commercial scale Wetox systems operating. However, a 200 lb ($\sim$ 91 kg) dry solids per day pilot plant scale Wetox unit (Model 4-10) has been in operation for almost three years. The assembled pilot plant reactor system with air compressor and sludge feed pump etc, is shown in Figure 10.

Most of the sludge destruction data were obtained through the experimentation with the pilot scale unit. Various types of sludge from different sewage plants have been tested under different Wetox process conditions. Table 5 lists the types of sludge tested. According to the technical information supplied by Barber-Colman Co., the optimum operating conditions for sludge destruction appear to be 450^{o}F and 600 psi ($\sim$ 232^{o}C and 4137 kPa); input sludge is dosed with sulphuric acid to 3 gm/litre. Reaction time is $\sim$ 40-60 minutes. Only slight excess over the stoichiometric amount of oxygen for oxidation is required. Up to 75-85% oxidation can be achieved. A typical Wetox performance curve is shown in Figure 11. It is evident from the Figure that most of the oxidizable COD disappears in the first 12 minutes of reaction time while the sludge is still in the first compartment of the reactor.

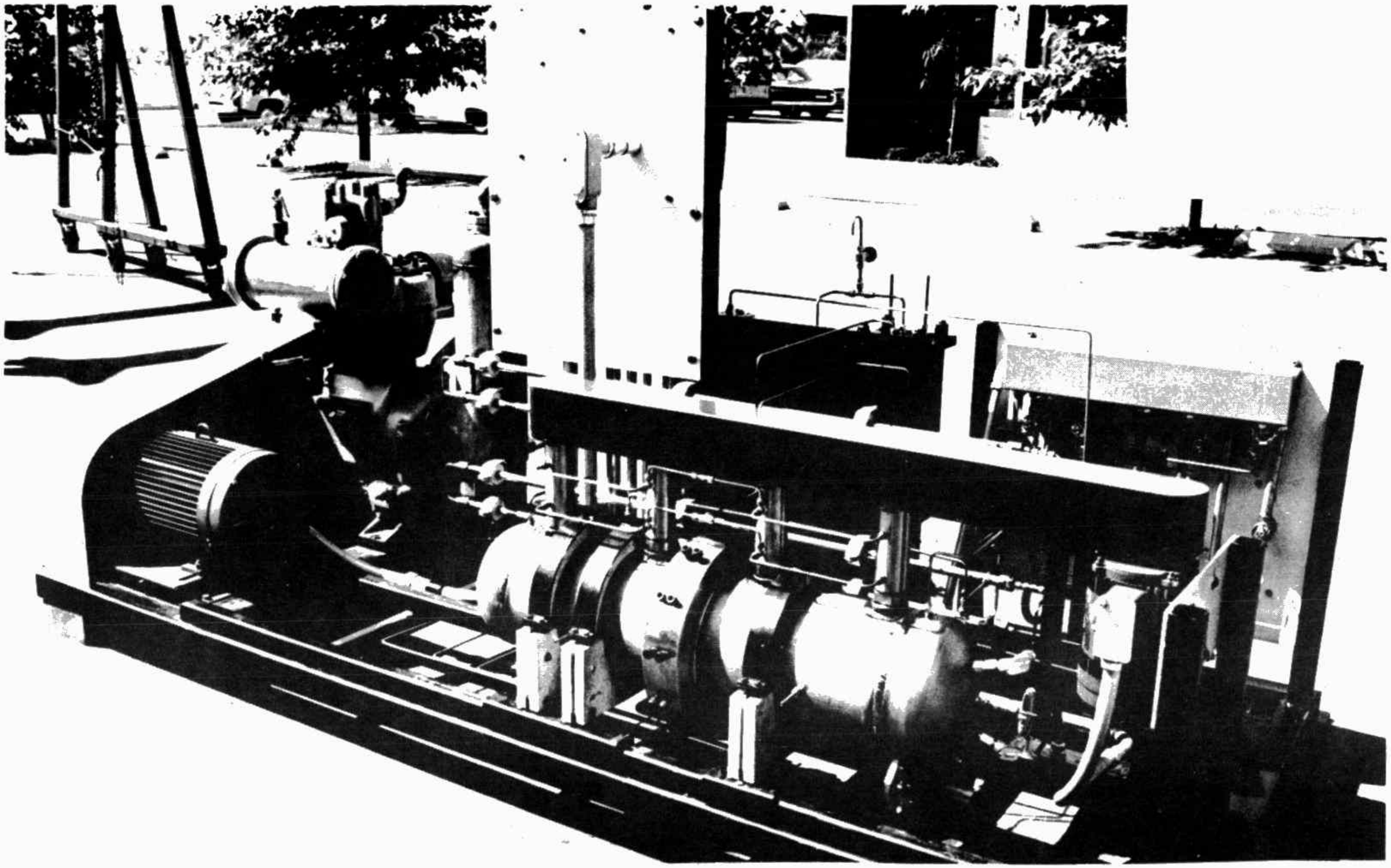


FIGURE 10. 0.1 TON (~0.09 METRIC TON) DRY SOLIDS PER DAY PILOT SCALE WETOX UNIT (MODEL 4-10).

TABLE 5. SLUDGES PROCESSED TO-DATE AT BARBER-COLMAN WETOX PILOT PLANT

Source	Type
Corona	Primary + W.A. Secondary
Indio	Primary + W.A. Secondary
Irvine	Primary + W.A. Secondary
	W.A. Secondary
Laguna	Primary
Los Angeles	Anaerobic Digester
New York City	Anaerobic Digester
Orange County	Primary
San Clemente	Primary + W.A. Secondary
S.E.R.R.A.	Anaerobic Digester
	Aerobic Digester

In these pilot plant runs, both the vapour and the liquid exiting from the Wetox unit are treated separately with lime to remove heavy metals, phosphates and ammonia etc. The condensed vapour phase is neutralized to 7 and then clarified. The liquid phase is neutralized to 11 and then clarified. The effluent from the Puretec System (i.e. Wetox plus lime treatment) has pollutant concentrations typically as shown in Table 6. If higher purity effluent is desired, reverse osmosis can be provided as an added option. Thus, based on the results obtained from these pilot plant experiments, Barber-Colman has issued the performance specifications on the Puretec System as shown in Table 7.

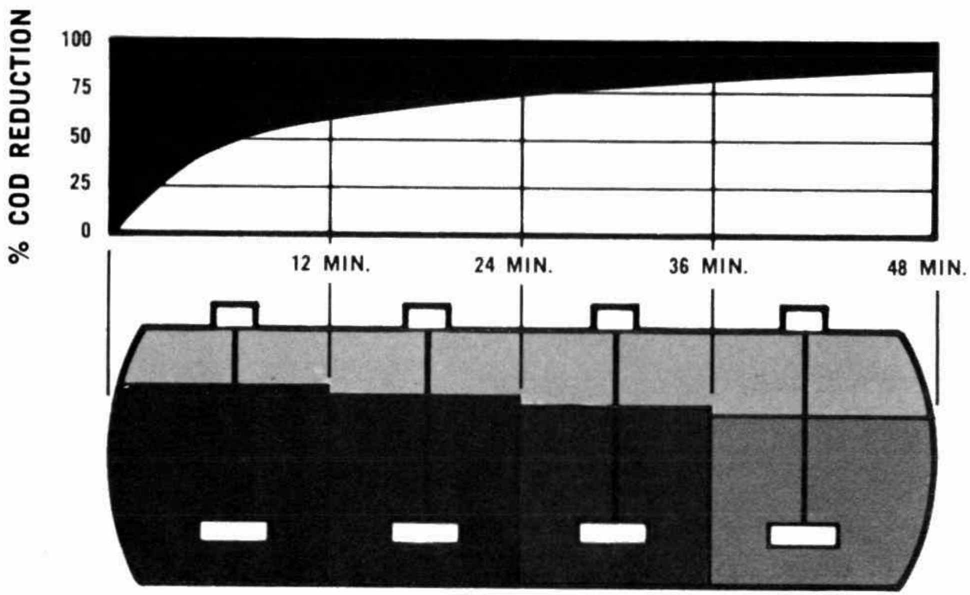


FIGURE 11. WETOX REACTOR PERFORMANCE.

TABLE 6. TYPICAL POLLUTANT IN PURETEC SYSTEM EFFLUENT.

Pollutant	Amount
C	25% of Influent
NH_3	< 3000 ppm
NO_3	< 2 ppm
PO_4	< 60 ppm
SO_4	< 1000 ppm
Ca, Mg	< 100 ppm
Metals	< 1 ppm
pH	6.5 - 7.0
Organic Solids	10% of Influent

TABLE 7. PURETEC SYSTEMS SPECIFICATIONS.

	Basic Systems (i.e. Wetox + Lime treatment)	With Options (e.g. reverse osmosis step added)
Organic Solids Reduction, %	90 - 95	95 - 99
Recycle Waters	Suitable for Recycling	
COD Reduction, %	75 - 85	85 - 95
Heavy Metals, ppm	< 1	< 1

4. ORF EVALUATION OF THE BARBER-COLMAN WETOX PROCESS

The original objective of this study was to gather and analyse the available technical and economic data on the Wetox process in order to evaluate the suitability of the process for sludge disposal. Comparisons were to be made between the Wetox and the Zimpro process because they are rather similar in operation. Since no commercial Wetox plant has yet been built, only the pilot plant data are available. Therefore, the evaluations are based on the risky assumption that the projected commercial Wetox plant operation and performance are similar to those of the pilot plant. It is almost certain that problems will arise during equipment scale-up, and the estimated economics of the commercial scale Wetox process based on pilot plant data can be considered, at best, approximate. Thus the conclusions derived from the comparison between the Wetox and the Zimpro process should be viewed as tentative.

The actual evaluation program consisted of the following steps:

- A detailed study was carried out of the literature plus special information on the Wetox process as supplied by Barber-Colman Co.
- A visit was made to Barber-Colman's Wetox pilot plant in Santa Ana, California on October 24th, 1973 to assess the pilot plant equipment, observe the Wetox unit in operation and gather the available performance data for the unit.
- A limited amount of experimental and analytical work was performed at ORF on oxidized sludge samples sent from Barber-Colman in order to evaluate and verify the claims made by Barber-Colman Co. on the Wetox performance and economics.

4.1 Reactor Design Evaluation

Much of the Wetox reactor design evolves from the mining industry in which wet air oxidation was first conducted commercially in 1952. The Wetox reactor is basically the same type of horizontal, compartmented autoclave first used by the Calera Mining Co. at Garfield, Utah (22). The inside of the reactor is illustrated in Figure 12. The optimum number of compartments in the autoclave depends on the size and desired efficiency of oxidation. Usually, for 30-60 minutes of sludge retention time, 4-6 compartment will suffice.

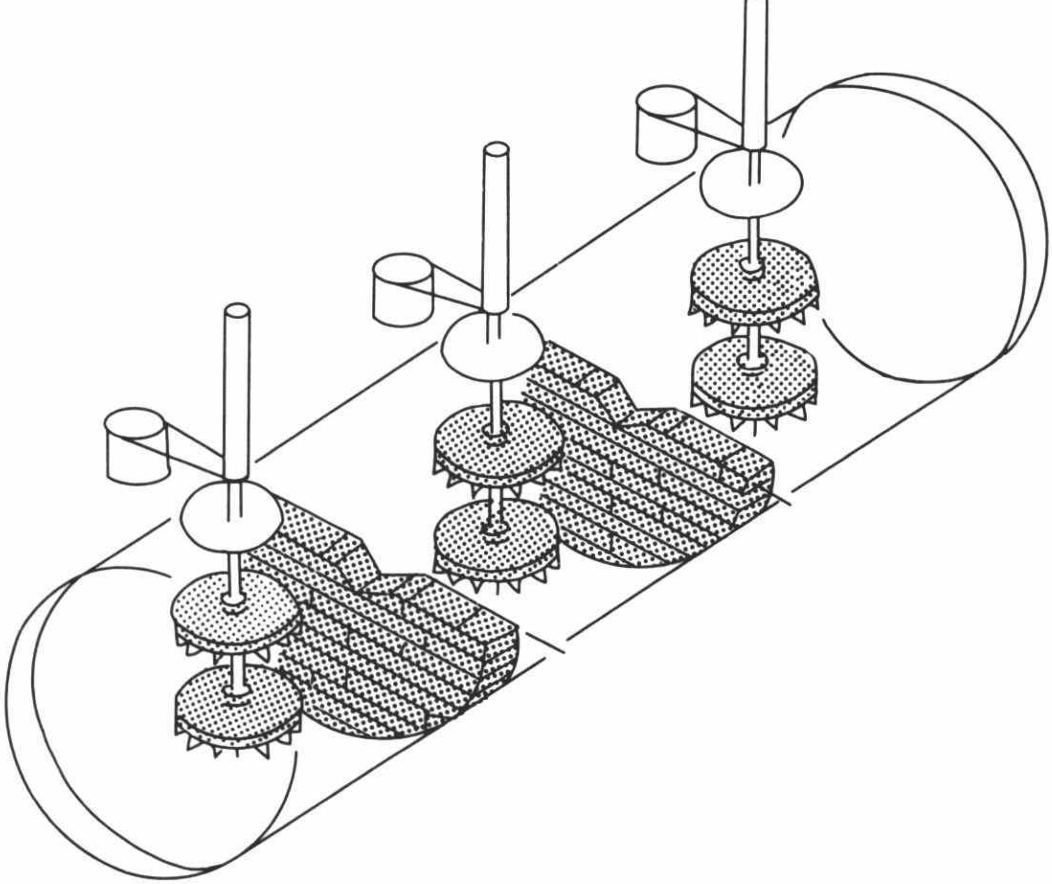


Figure 12

Wetox Reactor Design Based on Metallurgical Wet-Oxidation

The 450°F-600 psi ($\sim$ 232°C-4137 kPa) operating conditions are largely dictated by the cost-performance trade-off. Standard hardware such as pipes and flanges with 600 psi ($\sim$ 4137 kPa) ratings are off-the-shelf items. When operating at higher than 600 psi ($\sim$ 4137 kPa), the reaction vessel has to be rather thick and the pumping cost increases.

There are several features in the Wetox reactor design that distinguish the Wetox process from the Zimpro process. These features are:

a) Mechanical Mixing

b) Compartmented

c) Horizontal

d) Titanium or brick lining

Each feature is individually discussed in the following.

4.1.1 Mechanical mixing

Each compartment in the reactor is stirred individually. The effect of stirrer speed on sludge oxidation has been investigated by Barber-Colman in the range from 0 to 1500 rpm. The enhancement of oxidation by agitation is illustrated in Figure 13. Although the adequate stirrer speed is observed from the Figure to be at $\sim$ 750 rpm, the Company concluded that the optimum stirrer speed was $\sim$ 1200 rpm. Similar investigations carried out by Wheaton et al (23) also confirmed the positive effects of stirring on wet air oxidation.

Advantages of Stirring. Irrespective of the complicated reaction mechanism occurring during wet air oxidation as explained previously in Section 3.2, the overall reaction rate depends on the intimate mixing of gas-liquid-solid phases for maximum heat and oxygen transfer. Agitation disperses the air into the liquid as small bubbles, thus increasing the effective interfacial area for mass transfer; it circulates the liquid in swift eddy currents, delaying the escape of air bubbles from the liquid and keeping the solids in suspension, thus increasing the contact time for mass transfer; it also causes turbulent shear, thus reducing the thickness of the stagnant liquid film and, hence, resistance to mass transfer.

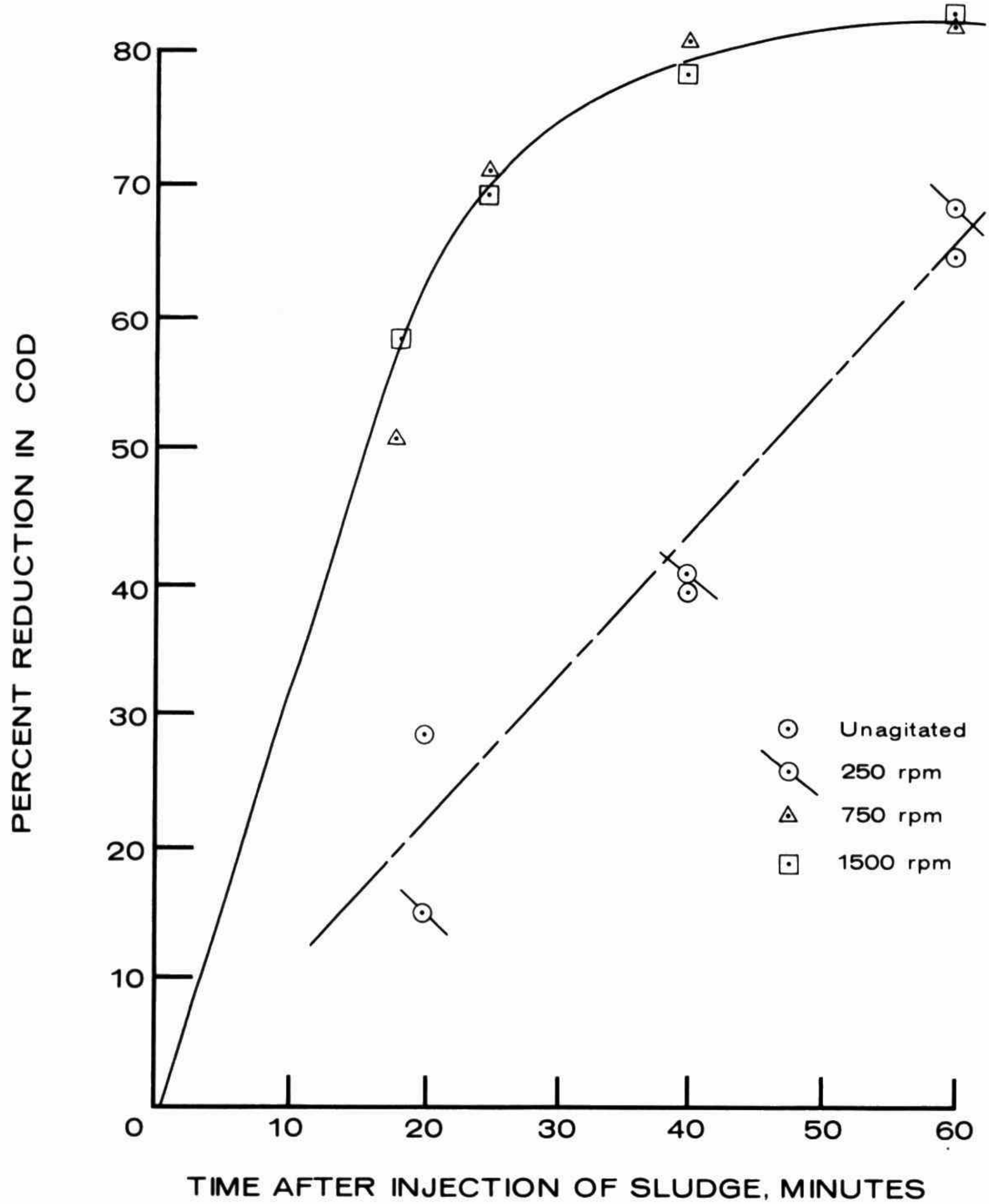


Figure 13

Effect Of Agitation In Wetox

Disadvantages of Stirring. The optimum stirrer speed for effective mixing was found by Barber-Colman to be at $\sim$ 1200 rpm. At this speed, frequent replacement of the packings around the stirrer drive shafts may be necessary. Neither the ordinary graphite nor teflon packing materials can stand the high speed rotation of the titanium stirrer very well. Extensive re-design work on the stirrer unit is being carried out to solve this problem. Ultrasonic stirring may be the answer; however, cost of stirring by this method may be high.

The stirring also requires the installation of motor and drive and all these add to the extra capital and operating cost of the operation.

4.1.2 Compartmented Reactor

The inside of the Wetox reactor is compartmented. Normally, for sludge destruction, 4-6 compartment design is used.

Advantages of Compartmented Reactor. A compartmented reactor is, in effect, equivalent to a number of individual small stirred reactors connected in series. This design would improve the reaction efficiency if the reaction order is positive, and minimize the possibility of short circuiting of the sludge stream.

The "compartment" design would also allow the selective injection of additives at certain stages of the reaction without affecting the operation in the preceding compartments. It also enables the reactor to operate under variable temperature in each compartment for specific reactions. Variable linings on the wall of individual compartments are possible for selected catalytic action. All these would add to the versatility and efficiency of the unit.

Disadvantages of Compartmented Reactor. Construction of reliable long-lasting partitions inside a pressure reactor is rather difficult and costly particularly when the reactor is operating under turbulent flow conditions and with a substantial amount of solids. Baffles will inherently increase the resistance to the flow and could increase the pumping cost.

In the present reactor design, the volatile organics, once flashed into the vapour phase, will mostly be swept out of the reactor without further chance of being destroyed because oxidation in the vapour

phase is slow. With a carefully controlled multiple air feeding system, the total air input is divided proportionally according to oxygen demand in each compartment, and fed separately into individual compartments under the stirrer. The flashing of volatile organics can be reduced.

4.1.3 Horizontal

The Wetox reactor is a horizontal, cylindrical pressure vessel as compared to the vertical Zimpro reactor.

Advantages of Horizontal Reactor. The horizontal position of the reactor (as well as the heat exchangers) means lower erection cost and easy accessibility for maintenance. In addition, by positioning the reactor near the ground level or even below ground (in a pit as shown in Figure 7), the operation is safer and more aesthetic.

Disadvantages. Horizontal reactor (as well as heat exchangers) will invariably occupy more space, thus increasing the cost of the plant building.

4.1.4 Reactor lining

Small size reactors, together with stirrers and baffles, are lined or made of titanium. For larger size reactors, such as those with the capacity of processing 16 tons ($\sim$ 14.5 metric tons) or more of dry solids per day, the reactor is made of steel shell but lined with acid resistant bricks.

Advantages of Lining. The choice of titanium (or acid resistant brick) as materials of construction eliminates the acid corrosion problems. Titanium vessels, in addition, are light weight, immune to chloride ion attack, have excellent abrasion resistance and can easily be fabricated. In larger vessels, brick lining on the steel shell is more economical than the equivalent titanium vessel. The brick lining adds to the insulation of the pressure vessel, and certain types of bricks may have a catalytic effect on the oxidation reaction.

Disadvantages of Lining. It is logical to suspect that titanium vessels are probably expensive although Barber-Colman claims that for many shapes and sizes of vessels, titanium actually has lower cost than 316 stainless steel and superalloys. As far as the brick lined vessels are

concerned, they are probably also expensive. The vessel would be quite heavy and subject to solids abrasion. More often than the normal repair schedule of the lining may be necessary.

4.2 Wetox Operation Evaluation

There are also several special features in the Wetox process operation that are different from the Zimpro process operation. They are:

a) Reaction in acid-medium
b) Phase separation at the reactor
c) Lime neutralization (and reverse osmosis option) as post-treatment step.
d) Addition of catalysts (optional)

Each feature is now discussed in the following.

4.2.1 Acid medium

In the Wetox process, sulphuric acid is added into the sludge prior to oxidation. Experience gained by Barber-Colman during the pilot plant study indicates that the optimum dosage of acid is 3 gm per litre of input sludge.

Advantages of Acid Addition. Addition of sulphuric acid to the sludge increases both the rate and the extent of sludge oxidation. This effect is evidenced from the results of the experiments performed at Barber-Colman as shown in Figure 14. The more acid is added, the higher is the rate of oxidation and the lower is the COD value in the effluent. Because of the acidic condition throughout the reactor system, the scaling problem associated with the reactor and heat exchangers of the Zimpro process does not occur.

Disadvantages of Acid Addition. Sulphuric acid is an expensive chemical costing $\sim$ \$36/ton ($\sim$ \$40/metric ton). Besides, addition of the acid increases the loading of sulphate ions in the treated effluent.

In addition, the acid will cause most of the heavy metals and probably most of the phosphates originally bound in the sludge to be leached out. As a result, an additional lime treatment step has to be installed to neutralize and precipitate heavy metals, phosphates and part

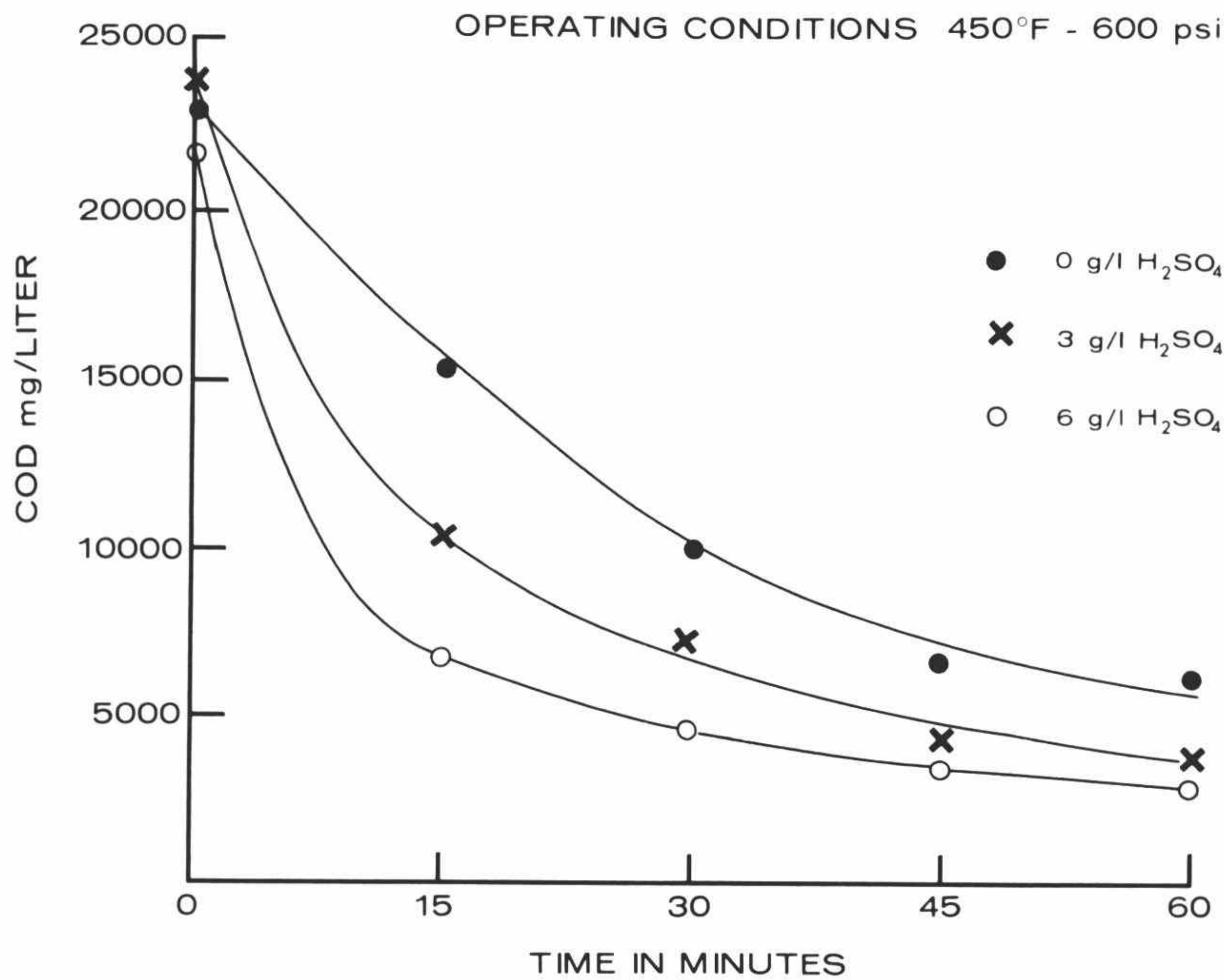


Figure 14

COD Reduction Of Orange County Sanitation District Primary Sludge

of the sulphate from the Wetox effluent before the supernatant liquid can be recycled back to the secondary treatment plant. Consequently, there is an economic trade-off between improved operation efficiency, with the accompanying lower capital and maintenance cost but high chemical cost, and vice versa. The company considers that the trade-off point is 3 gm of sulphuric acid per litre of input sludge.

4.2.2 Phase separation at the reactor

Under the operating conditons of 450°F and 600 psi (232°C and 4137 kPa) with approximately 10% of excess air over the required amount for the desired degree of oxidation, the volumes of the vapour and liquid effluent from the reactor are in the ratio of approximately 1:2. These two streams are separately drawn out from the last compartment in the reactor as depicted in Figure 6.

Advantages of Phase Separation. Separate withdrawal of a large volume of vapour and spent air from the last compartment of the reactor will increase the effective retention time of the sludge in the reactor. Moreover, this design will facilitate the subsequent post-treatment steps. For example, the volatile "grease" will stay with the vapour phase and be condensed and skimmed off, thus avoiding the co-mingling with the inert residue which is to be settled from the liquid phase and disposed. In addition, the liquid stream containing most of the impurities such as heavy metals, phosphates, sulphates and ammonia etc. are concentrated and more amenable to the lime treatment.

Another consideration at Barber-Colman is to utilize the vapour effluent for power generation. When a concentrated sludge is oxidized, a large amount of heat is generated in excess of that required to keep the system self-sustaining. The excess energy is carried out of the Wetox reactor mostly by the vapour phase which still contains a substantial amount of organics and trace amount of salts. Knowing the troubles that Zimpro encountered in its power recovery system with "dirty" vapour (Appendix I), Barber-Colman proposes to use a binary system heat exchanger. In the proposed scheme, the Wetox vapour effluent is passed through a heat exchanger to heat up de-ionized pure water. The pure steam thus generated is superheated to ∿ 900°F (∿ 482°C) by an external burner and expanded

through a turbine. Residual heat in the steam after expansion is further extracted by heat exchange with in-coming sludge in a second heat exchanger. The condensed pure water is returned to the first heat exchanger and completes the power cycle. With the conventional fuel cost escalating in recent months, the idea of power recovery becomes attractive. Nevertheless, a detailed technical and economic evaluation of such a recovery system should be made on pilot plant scale basis before commercialization is attempted.

Disadvantages of Phase Separation. Separate withdrawal of phases entails the use of separate heat exchangers. This approach invariably increases capital and operating costs. If a power recovery system is installed, an additional stationary engineer will probably be required for its proper maintenance.

4.2.3 Post-treatment steps

As indicated in the Wetox process flowsheet (Figure 6), the condensed vapour effluent is neutralized with lime to pH 7 and then clarified, while the liquid effluent is first neutralized to pH 7 and clarified to remove residual solids and heavy metals. Then the clarified liquid is further treated to pH 11 to remove phosphates by precipitation and ammonia, probably by air stripping.

If higher purity effluent is desired, reverse osmosis is provided as an added option.

Advantages of Post-Treatment Steps. The lime treatment is necessary in order to neutralize the free acid in the Wetox effluent before it can be recycled back to the secondary treatment plant. By neutralizing the liquid phase effluent in two steps, dissolved impurities can selectively be precipitated. At pH 7, all the heavy metals will be precipitated and settled together with inert solids for disposal. When the pH of the liquid is increased to above 9, ammonia can be stripped off and the phosphates are precipitated. The precipitated "lime sludge" from this stage, containing mostly lime and phosphates, may be suitable for use as fertilizer.

Further treatment of the effluent with reverse osmosis will, no doubt, upgrade the effluent to high quality.

Disadvantages of Post-Treatment Steps. Lime treatment will add to the capital and operating costs. Optional reverse osmosis will push the cost even higher. Under the present Wetox process conditions, lime treatment appears to be necessary in order to remove the acid, heavy metals, phosphates and nitrogen content from the Wetox effluent before the supernatant liquor can be recycled; otherwise build up of these pollutants in the overall sewage treatment circuit is unavoidable. Further upgrading of the effluent via reverse osmosis before recycling appears to be unnecessary.

The mixture of lime sludge and inert residual solids precipitated from the Wetox effluent contains perhaps 15% solids and may or may not pose problems for handling. The land disposal of this mixture should be further investigated.

4.2.4 Addition of catalysts (optional)

Barber-Colman Wetox process provides an optional use of catalysts as additives to enhance sludge destruction. A variety of catalysts is offered; some of these are soluble while others are added into the sludge as heterogeneous solids which can be recovered from the Wetox effluent stream for recycle. Little is known about the composition of the catalysts as the company claims that they are trade secrets. However, a literature review of wet air oxidation indicates that they are probably either simple or complex salts of copper, cobalt, manganese, zinc or chromium.

Advantages of Catalyst Addition. According to the information supplied by Barber-Colman, addition of catalysts appears to be effective. The company claims that under normal process conditions, up to 95-99% of organics oxidation is possible with catalysts as compared to 75-85% oxidation without catalysts.

Disadvantages of Catalyst Addition. The major reason for catalyst addition is probably the boosting of the sludge destruction almost to completion. Yet, this particular feature of complete sludge destruction is not overwhelmingly important to the operation of the sewage treatment plant, since they can recycle the Wetox effluent back to the secondary treatment system. Moreover, catalyst addition and subsequent recovery and reuse undoubtedly complicates the system and increases the cost.

It is logical to suspect that a small amount of the metal complexes will be leached out from the solid catalysts and they are usually bactericides. Unless these metal complexes can be completely precipitated, recycle of the Wetox effluent to the secondary treatment plant may disrupt its operation. Based on the aforementioned discussion, addition of catalysts to the sludge is probably not justified.

4.3 Wetox Performance Evaluation

A visit was made to the Barber-Colman pilot plant in Santa Ana, California on October 24th-25th, 1973. At the time of the visit, the Model 4-10 (0.1 tons or 0.09 metric tons of dry solids per day) pilot Wetox unit together with the lime treatment unit was in normal operation (i.e. $450^{o}F$, 600 psi [$\sim 232^{o}C$, 4137 kPa] and 3 gm sulphuric acid per litre of sludge). Several runs were made with raw sludges obtained from nearby sewage treatment plants. The entire Puretec System (i.e. Wetox plus lime treatment) operated automatically without any troubles. During each run, samples of the acidified raw sludge, Wetox effluents before and after lime treatment were taken and analysed. A set of these samples is shown in Figure 15. Also during the time of the visit, an independent feasibility study was carried out by Sunkist Co. for Barber-Colman to upgrade the quality of Wetox effluent via reverse osmosis. Samples of the upgraded effluent are also included in Figure 15. The following observations were noted from these samples.

- Vapour phase effluent from Wetox reactor (Sample #2 in Figure 15) ranged from milky to faint yellow in colour depending on the nature of the sludge used for that particular run. The milky colour was due to the presence of a small amount of emulsion of volatile grease reported by Barber-Colman to be generally in the carbon chain length up to C_{22}. In the case where the vapour phase effluent was faint yellow in colour, the grease had already separated from the liquid by itself and floated at the top.
- The liquid effluent from the Wetox reactor (Sample #5 in Figure 15) was brownish yellow in colour and contained a substantial amount of greyish black solids which settled readily.

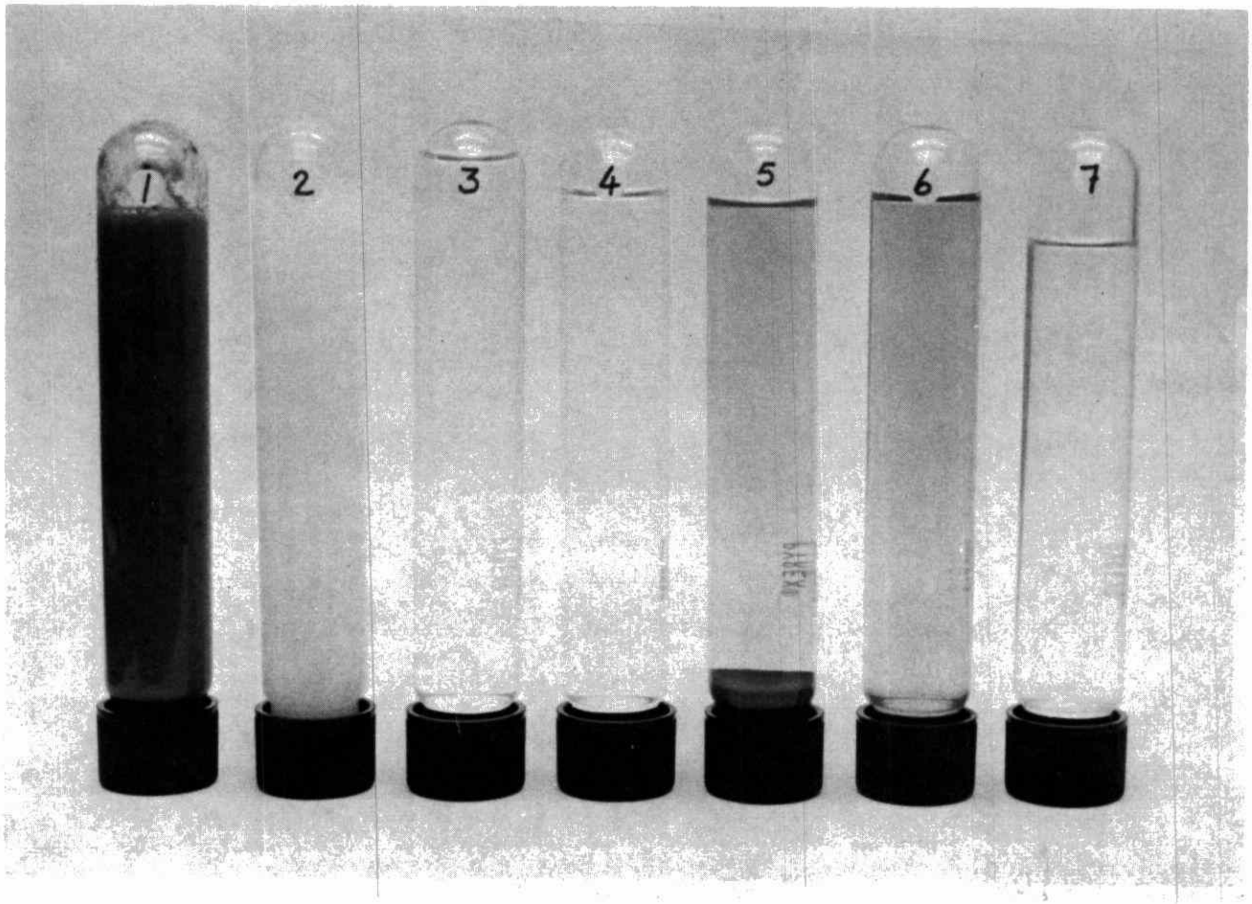


FIGURE 15. SAMPLES OF RAW SLUDGE AND WETOX EFFLUENTS.

1 - Raw Sludge

2 - Vapour Effluent from Wetox Reactor

3 - Vapour Effluent from Wetox Reactor after Lime Treatment

4 - Vapour Effluent from Wetox Reactor purified by Reverse Osmosis

5 - Liquid Effluent from Wetox Reactor

6 - Liquid Effluent from Wetox Reactor after Lime Treatment

7 - Liquid Effluent from Wetox Reactor purified by Reverse Osmosis

- The effluent after lime treatment (Sample #6 in Figure 15) was yellow in colour and free of suspended solids.

Laboratory analyses on samples obtained from a typical Wetox run were furnished by Barber-Colman as shown in Table 8. It became obvious from the table that Barber-Colman was more interested in studying the performance of the Puretec System (Wetox plus lime treatment) rather than the performance of the Wetox unit itself. Moreover, the performance was based mainly on the reduction of organics, phosphates and heavy metals.

It was decided that a set of samples from a normal run, consisting of raw sewage sludge plus Wetox effluents with and without lime treatment, should be analysed independently at ORF in order to (a) verify the claims of Barber-Colman and (b) find out the stage-by-stage performance of the Puretec System. Accordingly, a set of samples from a normal run randomly chosen by Barber-Colman was sent to ORF for analysis. The results are presented in Table 9. It should be emphasized, at this point, that the interpretation of sewage sludge analytical results is awkward. Representative samples are difficult to obtain from effluent streams containing both liquid and solids. Furthermore, variation in composition of sewage sludge is large even if the sludge is taken from the same treatment plant. Based on all these factors, it would be risky to draw any definite conclusions based on one set of analyses. Nevertheless, from Table 9, the superior performance of the reverse osmosis in upgrading the effluent quality is apparent.

In order to further evaluate the economics as well as the technical merits of the Puretec System, the lime treatment step to further purify the Wetox effluent was simulated in the ORF laboratory. Samples of the raw sludge, Wetox vapour and liquid effluents from another randomly chosen normal run were again sent to ORF. Various pollutant concentrations in these samples were analysed. Both the vapour phase and the liquid phase Wetox effluent were then neutralized separately with lime to pH 7 and then further treated to pH 11. The amount of lime required for each neutralization was noted. Samples were taken and analysed at each stage of neutralization. The lime requirement for these post-treatment steps is shown in Table 10. The pollutant concentrations at

TABLE 8. DISTRIBUTION OF VARIOUS POLLUTANTS IN INPUT AND OUTPUT STREAMS OF THE WETOX REACTOR (SAMPLE RUN #1)

Samples Analysed	pH	Total Solids (mg/kg)	COD (ppm)	TOC (mg/kg)	P (ppm)	Cu (ppm)	Ca (ppm)	Mg (ppm)	Zn (ppm)
Raw Sludge	-	45100	29484	10969	80	1.5	12.6	20.5	1.27
Liquid Effluent Neutralized With Lime	∿7	-	6938	4093	1.2	0.7	10.6	237.5	0.1
Vapour Condensate	6.6	-	8837	3470	0.3	-	0.1	1.3	-

Normal Wetox Process Conditions: $450^{\circ}F$, 600 psi (∿ $232^{\circ}C$, 4137 kPa)

3 gm of sulphuric acid per litre of input sludge

40 - 60 minutes retention time

TABLE 9. DISTRIBUTION OF VARIOUS POLLUTANTS IN INPUT AND OUTPUT STREAMS OF THE WETOX REACTOR (SAMPLE RUN #2).

Samples Analyzed	pH	*Total Solids (mg/kg)	Volatile Solids (mg/kg)	*COD (ppm)	*TOC (ppm)	SOC (ppm)	*TKN (ppm)	NH_4 (ppm)	NO_3 (ppm)	*Total PO_4 (ppm)	SO_4 (ppm)	Cl (ppm)	*Cu (ppm)	*Ni (ppm)	*Fe (ppm)	*Zn (ppm)
Raw Sludge	2.55	24813	16927	20085	5320	542	646	16.7	25.0	616	4520	125	9.4	1.6	38.0	82.0
Liquid Effluent	2.9	17648	7244	8197	2318	740	729	80.5	63.0	441	6280	95	10.0	1.8	48.0	89.2
Liquid Effluent clarified after lime neutral-ization	6.0	8241	3273	6800	2082	713	685	86.2	53.0	65.6	3020	138	3.7	0.4	0.4	1.2
Liquid Effluent purified by Reverse Osmosis	4.75	397	218	2000	276	145		2.9	16.0	3.6	92	44	0.2	0.1	0.4	0.35
Vapor Effluent	4.45	403	383	5160	1460	212		13.2	16.5	2.6	4	<1	0.1	0.1	0.6	0.35
Vapor Effluent clarified after lime neutral-ization	7.6	2257	1678	3280	1026	238		14.4	27.5	31.0	12	15	0.1	0.1	0.5	0.5
Vapor Effluent purified by Reverse Osmosis	7.3	60	60	1080	234	45		11.5	6.5	2.0	5	16	0.05	0.1	0.5	0.28

* Homogeneous sample of solid and liquid, if the stream contains two phases.

Normal Wetox Process Conditions: 450°F, 600 psi (~232°C, 4137 kpa); 3 gm sulphuric acid per litre input sludge; 40-60 minutes retention time.

TABLE 10. LIME REQUIREMENT (IN LB/LB OR GM/GM OF THE EFFLUENT) FOR NEUTRALIZATION OF WETOX EFFLUENT (SAMPLE CALCULATIONS ARE SHOWN IN APPENDIX III)

	Vapour Phase Effluent	Liquid Phase Effluent
Neutralization to pH = 7	.0012	.0027
Treatment from pH = 7 to pH = 11	.0006	.0023
Total Lime Requirement for treatment to pH = 11	.0018	.0050

each stage of neutralization in the Wetox effluent streams are shown in Table 11.

The three sets of data contained in Tables 8,9 and 11 were analysed. The results of the analyses are shown in Table 12. Some tentative conclusions can now be drawn about the performance of the Wetox unit as well as the Puretec System. These conclusions, however, should be verified with a few more sets of data to increase the confidence level.

When operating under the normal process conditions (i.e. $450^{o}F$ or $\sim 232^{o}C$, 600 psi or $\sim$ 4137 kPa, 3 gm of sulphuric acid per litre of sludge and 40-60 minutes of sludge retention time), the vapour and liquid effluents from the Wetox reactor were split in the ratio of 1:2. The vapour phase was relatively free of pollutants other than ammonia and organics; about half of the organics in the vapour phase were in the form of grease which can be skimmed off from the top of the vapour phase upon cooling. Most of the residual pollutants remained in the liquid phase effluent stream. On the overall basis (i.e. combining the two effluent streams together) it would appear that the Wetox alone can achieve $\sim$ 80% destruction of the suspended solids and 65-82% reduction of the total organics as well as the COD. Only $\sim$ 11% of the nitrogen compounds are destroyed and possibly reduced to nitrogen gas. Most of the nitrogen compounds are just converted to ammonia and a small amount is converted to nitrates. Heavy metals are probably leached out of the sludge. Phosphate analyses on these data proved to be inaccurate, therefore, no meaningful conclusions can be drawn about the distribution of phosphates. Logically, the phosphates should also be leached out under acidic conditions. When the Wetox effluents are neutralized with lime to pH 9-11, almost all the heavy metals and phosphates, part of the sulphates as well as any remaining suspended solids are precipitated. Thus the organics reduction may be improved to the 75-85% range which is in line with the range specified by Barber-Colman Co. for the performance of the Puretec System (Table 7; Section 3.4.3). Ammonia can be air stripped to a low concentration. Thus a combined stream from the Puretec System, containing perhaps 2000-5000 ppm of low molecular weight organic acids and 50-70 ppm of nitrates, will be recycled back

TABLE 11. DISTRIBUTION OF VARIOUS POLLUTANTS IN INPUT AND OUTPUT STREAMS OF THE WETOX REACTOR (SAMPLE RUN #3).

Samples Analyzed	pH	TDS (mg/kg)	Suspended Solids (mg/kg)	Total Solids (ppm)	TOC (mg/kg)	SOC (ppm)	TKN Homogeneous Sample (ppm)	TKN Liquid Sample (ppm)	NH_3 (ppm)	NO_3 (ppm)	Total PO_4 Homogeneous Sample (ppm)	Total PO_4 Liquid Sample (ppm)	Grease (ppm)
Raw Sludge	2.8	11704	28640	40344	30000	-	997	672	430	25	1060	900	-
Liquid Effluent	3.1	12294	8602	20896	5830	4370	1221	1102	905	105	775	35	-
Liquid Effluent neutralized with lime to pH 7	7	9860	13272	23132	5970	3930	1136	1003	902	150	547	9.0	-
Liquid Effluent treated with lime to pH 11	11	10764	15768	26532	5830	3930	819	789	648	90	230	<1	-
Vapor Effluent	4.2	220	1	221	2930	-	230	230	-	24	<1	<1	2372
Vapor Effluent neutralized with lime to pH 7	7	3606	~0	3606	2900	-	224	224	-	12	<1	<1	-
Vapor Effluent treated with lime to pH 11	11	6194	~0	6194	3270	-	203	203	-	53	<1	<1	-

Normal Wetox Process Conditions: 450°F, 600 psi (~232°C, 4137 kpa); 3 gm sulphuric acid per litre of input sludge; 40-60 minutes retention time.

TABLE 12. SUMMARY OF IMPORTANT RESULTS IN TABLES 8, 9, AND 11

% Reduction \ Sample Run No.	1	2	3
Suspended Solids (Wetox only)			80
Volatile Solids (Wetox only)		71	
Volatile Solids (Wetox with lime neutralization to pH = 7 and decantation)		84	
COD (Wetox only)		64	
COD (Wetox with lime neutralization to pH = 7 and decantation)	74	72	
TOC (Wetox only)	65	62	82
TKN (Wetox only)			11
TKN (Wetox with lime treatment to pH = 11 but without air stripping)			38

to the secondary treatment plant. Since the sludge stream usually amounts to less than 1% of the total flow in a sewage treatment plant, the adverse effects of the recycled stream on the secondary treatment effluent should be tolerable. It is not clear whether or not the non-condensable gases exiting from the Wetox have to be incinerated before discharge into the atmosphere. If this is proven to be the case, an after-burner will have to be installed.

4.4 Economic Analysis

Having gathered all the available technical details of the process, the economics of sludge disposal via the Puretec System (i.e. Wetox plus lime treatment) was estimated. The total cost, on per ton dry solids basis, calculated for the Puretec System was then compared with the total cost incurred when the sludge was processed via a Zimpro System.

It should be stressed that these estimates are based on the total cost of operating a complete disposal system from digested sludge to the ultimate land disposal of the residual solids; they are not based on the cost of operating a single treatment step. The costing of the Puretec System is based on economic data obtained from Barber-Colman towards the end of 1973.

4.4.1 Sludge disposal by Puretec System

The complete sludge disposal by Puretec System is based on the following process scheme:

- The raw sludge is processed through the Wetox unit at $450^{\circ}F$, 600 psi ($\sim 232^{\circ}C$, 4137 kPa) with sulphuric acid concentration of 3 gm/l.
- The effluents from the Wetox are neutralized to pH 9-10, air stripped to remove ammonia and pumped into a nearby lagoon for settling of solids.
- The supernatant liquor from the lagoon is recycled back to the secondary treatment plant.

Table 13 summarizes the total cost to operate a hypothetical 100 dry tons ($\sim$ 91 metric tons) per day Puretec plant for sewage sludge disposal. Detailed sample calculations of the cost estimates are

TABLE 13. PURETEC SYSTEM COSTS.

(Based on Processing 100 tons [∿ 91 metric tons] Dry Solids per Day 365 Days Per Year; Sample calculations are shown in Appendix II)

Items	Cost Per Day In $
Installed Plant Cost:	
Complete with full heat recovery, building, etc. as quoted from Barber-Colman Co. is $2.0 million *	
Add 10% contingency cost including ammonia stripping, extra piping to the lagoon and recycle lines etc. $2.2 million	
• Amortization at 8% interest rate over 20 years equipment life plus tax and insurance totals 12.2% per year; plus an additional $2000 interest on operating capital	741
Operating Cost	
• Electric Power at 400 kwh/ton (1587 MJ/metric ton) (information supplied by Barber-Colman in Dec. 1973)	400
• Chemicals (Sulphuric acid and lime)**	400
• Labour (assuming 1 supervisor, 3 shifts operation with 2 operators and a full time man on mechanical maintenance per shift; salary plus benefits at $16,000/year per man)	596
• Maintenance (assume 4% of plant cost per annum)	241
Total Cost Per Day Operation	2378
Total Cost Per Ton Dry Solids	24
Total Cost Per Metric Ton Dry Solids	∿ 26
There is approximately 754 x 10^6 Btu (795 x 10^6 kJ) recoverable. If this heat can be used for process heat or plant heating, at 60¢/million Btu, (∿ 57¢/million kJ)	452
∴ With full heat recovery (equipment already included), cost per dry ton of sludge disposal may be as low as	19
cost per metric ton may be as low as	∿21

* Note: Estimated Capital Cost of the Puretec System (With heat exchange only between incoming sludge and reactor effluent) is ∿ $1.5 million.
Building cost not included.

** Note: Sample calculations are shown in Appendix III

shown in Appendix II. While it is fully realized that the size of the plant chosen for the cost estimation is probably big as compared to the normal size of the treatment plants in Ontario, the choice was not arbitrary but was made for the following two reasons:

- The first Canadian Zimpro plant is scheduled to be installed in late 1974 at Lakeview Sewage Plant; it has a capacity of ~ 100 dry tons (~ 91 metric tons) per day.
- The total cost in operating the Puretec plant can be compared directly with that of the 100 dry tons (~ 91 metric tons) per day Zimpro plant in Kalamazoo, Michigan which is well publicized for its efficiency and economy.

As evidenced from the itemized list of cost estimates in Table 13, the assumptions made in arriving at these cost figures are quite arbitrary and may vary according to the prevailing local circumstances such as the interest rates, hydro and labour rates, etc. For example Table 14 illustrates the variation of cost estimates when the Puretec System is operated under slightly different sets of circumstances. The cost ranges between $21 to $34 per dry ton (~ $23 to $37 per metric ton). There are many unknowns involved in the estimation. As an example, it is still not clear whether or not an after-burner has to be installed to incinerate the non-condensable gases before discharging into the atmosphere. Only major expenditure items are included in the cost estimation; other "hidden" costs may exist. For these reasons, it is, therefore, logical to consider these cost figures as "rough" estimates.

4.4.2 Sludge disposal cost comparison between Puretec and Zimpro Systems

Cost information on the operation of three Zimpro sludge disposal plants have been obtained through either literature search or personal plant visits. These plants all operate under different process conditions. and with different post-treatment steps for the ultimate disposal of solids. Their cost figures are, therefore, individually compared with those estimated for the hypothetical commercial Puretec Systems of corresponding sizes.

TABLE 14. VARIATION OF COST ESTIMATES FOR 100 DRY TONS ($\sim$ 91 METRIC TONS) PER DAY PURETEC SYSTEM UNDER DIFFERENT CIRCUMSTANCES

Circumstances Different From Those Specified in Table 13.	Total Cost Per Ton Dry Solids Processed in $	Total Cost Per Metric Ton Dry solids processed in $
None	24	$\sim$ 26
Plant operating at 60% capacity and processing only 60 dry tons per day; but no reduction in operating staff.	34	$\sim$ 37
Equipment amortization is at 6% interest rate over a life period of 25 years totaling 7.823% per annum.	21	$\sim$ 23
Equipment amortization is at 6% interest rate over a life period of 25 years, totaling 7.823% per annum. (Similar to the rate used by Kalamazoo Plant). Plant processing only 60 dry tons per day but no reduction in staff. (This situation is similar to the 60% capacity operation in Kalamazoo Zimpro Plant).	30	$\sim$ 33

4.4.2.1 Kalamazoo Plant (Design capacity is 100 dry tons [∿ 91 metric tons] per day). According to the cost data obtained from the literature (8) as well as from personal plant visit (Appendix I), the total cost to run the Kalamazoo solid disposal system (i.e. Zimpro wet oxidation at 350^{o}F and 400 psi [∿ 177^{o}C and 2758 kPa] vacuum filtering dewatering-incineration) is \$32/ton (∿ \$35/metric ton) dry solids in 1973. Plant amortization in this cost estimate is \$10 per ton (∿ \$11 per metric ton) based on 90% operating capacity. If adjusted to 60% operation capacity, the plant amortization cost becomes \$15 per ton (∿ \$17 per metric ton). Total cost to run the Kalamazoo system is then \$37 per ton (\$41 per metric ton). However, this cost figure is higher than the optimum cost because the Zimpro plant was only operating at ∿ 60% capacity. Assuming that the hypothetical Puretec Plant is also running at 60% capacity, the corresponding total cost is estimated to be ∿ \$30/ton (∿ \$33/metric ton) dry solids. Thus, despite the added chemical requirements, the Puretec system should still have a lower total cost than the Zimpro System mainly due to its lower capital as well as labour costs.

4.4.2.2 Akron Plant (Design capacity is 50 dry tons [∿ 45 metric tons] per day). According to the information obtained through personal plant visit (Appendix I), the operating cost to run the Akron solid disposal system (i.e. Zimpro wet oxidation at 525^{o}F and 1600 psi [∿ 274^{o}C and 11032 kPa] - lagoon for dewatering) is estimated at \$38/dry ton (∿ \$42/metric ton). At present, the plant is only operating at 50% capacity. It is expected that with 100% capacity operation, the operating cost can be cut down to ∿ \$32 per dry ton (∿ \$35 per metric ton). Plant amortization (at 6% interest rate) is estimated at \$16 - \$32/dry ton (\$18-\$35/metric ton) depending on whether full or 50% capacity operation is assumed. Thus total cost of \$48/dry ton (∿ \$53/metric ton) is arrived at if the plant is operating at full capacity and \$70/dry ton (∿ \$77/metric ton) if operating at half capacity.

Total cost for a 50 dry tons/day (∿ 45 metric tons/day) Puretec System at full and at half capacity is estimated at \$31 and \$55 per dry ton (∿ \$34 and \$61 per metric ton), respectively. This estimation assumes that a 50 tons/day plant requires the same number of operators as a 100 tons/day plant.

It is also interesting to note that both the pilot plant Puretec System and the Akron solid disposal plant give comparable organic destruction efficiency.

4.4.2.3 Hockford Plant (Design capacity is 3 dry tons [~ 2.7 metric tons] per day). According to published literature, the Hockford Sewage Works in England disposes of its sewage sludge by a combination of Zimpro Wet Oxidation at 480°F (~ 249°C) and 1200 psi (~ 8274 kPa) and dewatering of the oxidized sludge on conventional drying beds. The operating cost of such a disposal system is estimated at $30/dry ton (~ $33/metric ton). Amortization of the plant at 8% interest rate is $44/dry ton (~ $49/metric ton). Thus a total cost of $74/dry ton (~ $82/metric ton) is calculated if the plant is operating at full capacity. It is noted that the cost of electricity at the Hockford Plant is particularly high at $16/dry ton (~ $18/metric ton) of solids processed.

Total cost for a 3 dry tons/day (~ 2.7 metric tons/day) Puretec System operating at full capacity is estimated to be $52 per dry ton or ~ $57 per metric ton. (Plant amortization at 8% interest rate over 25 years is used as in the Hockford Plant cost estimation.) If amortization at 6 % interest rate is assumed, the cost is reduced to $48 per dry ton (~ $52 per metric ton). For such a small capacity, a semi-batch Puretec System may be used.

4.4.2.4 Summary of economic analysis. Cost comparison between Zimpro plants and the hypothetical Puretec Plants of similar sizes indicates that the Puretec System can provide satisfactory sludge disposal at a relatively lower cost than the Zimpro System. Indeed, the disposal cost range of $21-$34 per ton (~ $23-$37 per metric ton) dry solids offered by the Puretec System is comparable to other more common conventional disposal processes (Table 2). This conclusion should be considered as tentative until a commercial scale Puretec Plant has been built and the operating cost estimated in this study has been verified. It should also be realized that the plant amortization cost in the three Zimpro plant estimates are based on unadjusted original plant costs (1969-1971).

In either Zimpro or Puretec Systems, unit disposal cost appears to increase with decreasing plant size; yet, the rate of increase for the Puretec System may be smaller, thus making it more favourable for small scale operation.

4.5 Further Comments

In addition to the sludge disposal, it appears that the Wetox system has high potential for industrial waste destruction, because it offers the following two advantages in addition to the usual waste destruction with heat recovery which is inherent in all types of wet air oxidation systems.

- Flexibility in the size and the operation of the Wetox system to handle a variety of industrial as well as municipal wastes. Continuous or semi-batch, small or large Wetox systems, processing corresponding volumes of wastes, respectively, are equally efficient.
- Resistance to both acid and alkaline corrosion. The corrosion resistant equipment renders the Wetox System ideal for processing wastes over a wide range of pH.

On the other hand, there are some foreseeable problems involved in the marketing of the Wetox Process. They are outlined in the following:

(a) Keen marketing competition

Judging from the recent contract awards for building municipal sludge disposal systems, the trend is towards low temperature and pressure sludge conditioning with subsequent dewatering and incineration. It is not clear whether this trend is caused by the fact that there is no satisfactory high pressure and temperature sludge oxidation system on the market at a reasonable cost or by some other advantages of the combination system.

Nevertheless, in order to break into the market, Barber-Colman has to compete with established companies such as Zimpro, Zurn, Envirotech etc. However, if Barber-Colman can demonstrate that the Wetox process is lower in cost to other sludge conditioning systems and has simpler process operation, the future potential for Wetox systems should be high particularly for small communities where land spreading of sludge is unsuitable.

(b) Shortages in Materials of construction

Because of rapid capital equipment expansion by industry in recent months, materials of construction are generally in short supply. Delivery of high pressure steel and titanium, which are essential for the Wetox unit, is quite slow. Other basic hardware such as motors, pumps etc. are difficult to obtain.

(c) New Company in sludge disposal market

Although Barber-Colman Company, founded in 1894, is a diversified manufacturer of hundreds of different products for world-wide industrial and commercial use, the Resource Recovery Systems Division which pioneered the Wetox process was only established in 1971. Development of the Wetox System has so far been mostly financed by the parent company although several external contracts to study the feasibility of applying the Wetox for shipboard waste treatment and for destruction of military wastes have been awarded by the U.S. Navy and the U.S. Coast Guard. Several test units have been built under these contracts.

At the present time, Barber-Colman Company is negotiating with the U.S. EPA in seeking financial support to build a Wetox Demonstration Plant. Several meetings have been held between the two parties. According to Barber-Colman, the U.S. EPA has included a plant scale Wetox demonstration in its 1975 fiscal years's funding and is in the process of selecting a suitable municipality, possibly Philadelphia for the plant. It is, therefore, logical to expect that there will be at least a time lapse of about one year before the Wetox process can be demonstrated on commercial scale.

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- South Peel Sewage Treatment Plant (M. Thorne, Assistant Engineering Manager)

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APPENDIX I

SUMMARY OF ZIMPRO PLANT VISITS

APPENDIX I

SUMMARY OF ZIMPRO PLANT VISITS

(a) Kalamazoo Sewage Treatment Plant (November 19, 1973)

- Contact

L. Pratt, Plant Superintendent; H. Gay, Zimpro Unit Supervisor.

- Purpose

To observe and evaluate the low temperature ($350^{\circ}F$ or $\sim 177^{\circ}C$) and low pressure (400 psi or $\sim$ 2758 kPa) Zimpro Unit Operation for sludge conditioning and to gather technical and economic data.

- Evaluation

Plant capacity is 100 tons ($\sim$ 91 metric tons) dry solids/day with three parallel reactor units at a total capital cost of $2 million (1969). Including building, dewatering equipment and incinerator, the total cost is approximately $4 million. Presently, the plant is running at 60% capacity, 17-31% solids reduction and little (5-10%) COD reduction. The conditioned sludge is dewatered via vacuum filtering. Filter cakes containing 45% solids are incinerated in a 7-hearth furnace at $1450^{\circ}F$ ($\sim 788^{\circ}C$). Supernatant liquor from the filter is recycled back to the secondary treatment unit. Heat addition is required for both the wet oxidation and the incineration.

24 hour wash of the heat exchanger with 5% nitric acid is required once every 6-8 weeks. Operating cost is estimated at $22/ton ($\sim$ $24/metric ton) plus $10/ton ($\sim$ $11/metric ton) on equipment amortization, assuming that the interest rate is 6% over a period of 25 years totalling 7.823% and the plant is operating at 90% capacity. Total cost is $\sim$ $32/ton ($\sim$ $35/metric ton) of dry solids. Operational problems include:

- Plugging of heat exchanger
- Sludge grinders need frequent repairs
- Heavy solids and COD recycling; thus overloading the secondary treatment facility.

Plant personnel express satisfaction with Zimpro Co. on its speed of servicing the units and the co-operation in solving any operational problems.

More detailed technical and economic data of this plant is available at the ORF.

(b) Akron Sewage Treatment Plant (November 21, 1973)

- Contact

J. White, Superintendent; B. Ryan, Assistant Plant Superintendent.

- Purpose

To observe and evaluate the high temperature ($525^{o}F$ or $\sim 274^{o}C$) and high pressure (1600 psi or $\sim$ 11032 kPa) Zimpro unit operation for sewage sludge disposal and to gather technical and economic data.

- Evaluation

Plant capacity is 50 tons ($\sim$ 45 metric tons) dry solids/day with two parallel reactor units at a total capital cost of $2.75 million (1970). Presently the plant is running at 50% capacity. Influent sludge is adjusted to pH 8.2 with caustic. 82% solids reduction and 75% COD reduction is achieved. At this high level of oxidation, the reaction is self sustaining without external addition of heat. The ash and liquor from the reactor are pumped into a lagoon for solids settling. The supernatant liqour is recycled to the activated sludge treatment plant. Vapours and gases from the reactor are passed through a separator to filter out solid impurities, then passed through 5% palladium catalyst to oxidize the remaining organics. The superheated vapours and gases after catalytic oxidation are expanded through a turbine which is hooked to a blower to furnish low pressure air for the secondary treatment plant.

At present, the plant is operating alternately with the two reactor units - one unit is on for $\sim$ 30 days and then shut off for 4-10 days to clean the heat exchangers with 5% nitric acid or chelating agents and to clean the reactor mechanically. Major maintenance (shut down for $\sim$ a month) is required for each reactor unit twice a year.

At 50% capacity the operating cost is estimated at $38/tons ($\sim$ $42/metric ton). It is expected that with both reactor units running, the cost may be cut down to $\sim$ $32 per ton ($\sim$ $35/metric ton). Capital equipment amortization is estimated at $16-$32/ton ($\sim$ $18-$35/metric ton) of dry solids disposed depending on whether full or 50% capacity operation is assumed. Operational problems include:

- Plugging and scaling of heat exchangers
- Scaling and caking of reactors.

- High pressure sludge pumps need frequent replacement of bags and ball check valves
- The separator to filter out solid impurities from vapours and gases is inefficient; thus the solids plug up the catalyst bed and foul the turbine
- Frequent replacement of pressure control valves

Plant personnel express satisfaction with Zimpro Co. on its speed of servicing the units and the co-operation in solving any operational problems.

More detailed technical and economic data of this plant is available at the ORF.

APPENDIX II

SAMPLE CALCULATIONS ON WETOX SYSTEM COSTS

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SAMPLE CALCULATIONS ON WETOX SYSTEM COSTS

These calculations are based on processing 100 tons ($\sim$ 91 metric tons) dry solids per day, 365 days per year.

- Amortization of Plant Cost

Amortization of a \$2.2 millions Wetox plant at 8% interest rate over 20 years life is 10.2% of investment per annum. Taxes and insurance of 2% giving a total of 12.2% of investment. An additional \$2,000.00 interest on operating capital is allowed.

Thus the amortization of plant cost per day is \$\{ 2200000 x .122 + 2000 \}/365 = \$741

- Electric Power

Electric power usage is estimated by Barber-Colman to be 400 kwh/ton or $\sim$ 1587 MJ/metric ton solids.

∴ To process 100 tons ($\sim$ 91 metric tons) of solids required (400 x 100) = 40000 kwh or (1587 x 91)= 144417 MJ. Assume a hydro rate of 1¢/kwh (0.278¢/MJ), cost of electricity per day is \$400.

- Chemicals

Cost of chemicals has been determined in Appendix III to be \$4 per ton ($\sim$ \$4.4/metric ton) dry solids.

∴ Cost of chemicals per day = \$4 x 100 or (\$4.4 x 91) = \$400

- Labour

Assuming 1 supervisor, 3 shifts round the clock operation, with 2 operators and a full time man on mechanical maintenance per shift: each shift works for 40 hours per week and the operation is carried out 7 days a week: salary plus benefits at \$16,000/year per man.

∴ Total number of men \{7 x 24/40\} x 3 + 1 = 13.6

∴ Total daily labour cost = (13.6 x 16,000)/365 = \$596

- Plant Maintenance

Assuming 4% of plant cost per annum,

∴ Daily cost = (0.04 x 2200000)/365 = \$241

Total Cost per day operation is (741 + 400 + 400 + 596 + 241) = \$2378

- Total cost per ton dry solids = \$24
- Total cost per metric ton dry solids = $\sim$ \$26
- <u>Heat Recovery</u>

Assuming an average fuel value of 7180 Btu/lb (16701 kJ/kg) of primary and secondary sludge solids mixture,

$\therefore$ 100 tons ($\sim$ 91 metric tons) of solids at 75% oxidation will generate $100 \times 2000 \times .75 \times 7180 = 10.77 \times 10^8$ Btu or $90718 \times .75 \times 16701$ $= 11.36 \times 10^8$ kJ

Assuming a 70% heat exchanger efficiency,

$\therefore$ Heat recoverable is $(.70 \times 10.77 \times 10^8) = 754 \times 10^6$ Btu/day or $(.70 \times 11.36 \times 10^8) = 795 \times 10^6$ kJ/day.

Assuming 60¢/million Btu ($\sim$ 57¢/million kJ),

$\therefore$ Return for heat produced is \$(754 x .6) or (795 x .57) = \$452/day.

$\therefore$ With full heat recovery, cost of sludge disposal per day is (2378 - 452) = \$1926

APPENDIX III

SAMPLE CALCULATIONS ON THE REQUIREMENT AND COST OF CHEMICALS

APPENDIX III

SAMPLE CALCULATIONS ON THE REQUIREMENT AND COST OF CHEMICALS

Data for the calculations are taken from lime neutralization experiments performed at ORF on the Wetox effluent samples sent by Barber-Colman.

- Vapour Phase Neutralization

pH of the vapour phase = 4.3

2.4 litres of the vapour phase require the addition of 2.904 gm of CaO in order to bring the pH of the solution to 7.

$\therefore$ Lime requirement is 2.904/2400 = .0012 gm/gm vapour phase effluent.

2 litres of the neutralized (pH = 7) vapour phase require the further addition of 1.21 gm of CaO in order to bring the pH of the solution to 11.

$\therefore$ Lime requirement is (1.21/2000) = .0006 gm/gm of vapour effluent.

$\therefore$ Total lime requirement to treat the vapour phase Wetox effluent. to pH 11 is (.0012 + .0006) = .0018 gm/gm effluent.

- Liquid Phase Neutralization

pH of the liquid phase is 3.1

2.4 litres of the liquid phase require the addition of 6.446 gm of lime in order to bring the pH of the solution to 7.

$\therefore$ Lime requirement is (6.446/2400) = .0027 gm/gm effluent.

2 litres of the neutralized (pH = 7) liquid phase require the further addition of 4.688 gm CaO in order to bring the pH of the solution to 11.

$\therefore$ Lime requirement is (4.688/2000) = .0023 gm/gm effluent.

$\therefore$ Total lime requirement to neutralize the liquid phase Wetox effluent to pH 11 (.0027 + .0023) = .0050 gm/gm effluent

- Cost of Lime to Process One Dry Ton ($\sim$ .91 Metric Ton) of Sludge with Both Phases Treated to pH = 11

Assuming the sludge contains 4% solids;

$\therefore$ For 1 ton ($\sim$ .91 metric ton) of sludge solids, there are 24 tons (21.8 metric tons) of water. According to information supplied by Barber-Colman as well as obtained from open literature, at 450°F and 600 psi ($\sim$ 232°C and 4137 kPa) the ratio of vapour to liquid phases in the Wetox effluent is 1:2.

∴ There are 8 tons (∼ 7.3 metric tons) of vapour phase and 16 tons (∼ 14.5 metric tons of liquid phase Wetox effluent.

∴ Total lime required = (8 x .0018 + 16 x .0050) = .094 tons or (7.3 x .0018 + 14.5 x .0050) = ∼ .086 metric tons.

∴ Total cost of lime (at $19/ton or at ∼ $21/metric ton) is $1.8

- <u>Cost of Sulphuric Acid to Process One Dry Ton (∼ .91 Metric Ton) of Sludge</u>

  Assuming the sludge contains 4% solids.

∴ For 1 ton (∼ .91 metric ton) of sludge solids, there are 25 tons (∼ 22.7 metric tons) of sludge. The dosage of the acid is 3 gm/litre of sludge, and assuming the density of the sludge is 1 gm/cc, then the amount of sulphuric acid required is (3/1000) x 25 = .075 tons or (3/1000) x 22.7 = .068 metric tons.

∴ Total cost of sulphuric acid (at $36 per ton or at ∼ $40 per metric ton) = $2.7

- <u>Requirement and Cost of Chemicals</u>

In the case of processing 4% sludge with the vapour phase and the liquid phase Wetox effluent treated to pH - 11, the requirement and cost for one ton (∼ .91 metric ton) of dry solids is $(1.8 + 2.7) = $4.5.

In a similar way, the requirement and cost of chemicals can be determined for processing 6% sludge and for lime treatment of Wetox effluents to different pH levels.

Table 15 illustrates the variation of chemical costs under different processing conditons. From this table a total chemical cost of $4 per dry ton (∼ $4.4/metric ton) is interpolated, for processing 4% sludge under normal operating conditions with the Wetox effluent neutralized to pH 9-11.

TABLE 15. CHEMICALS, DOSAGES AND COST ESTIMATES PER TON (~ .91 METRIC TON) OF SLUDGE SOLIDS PROCESSED BY THE WETOX REACTOR

Wetox Process Operating Conditions	H_2SO_4 Required (Tons)	(Metric Tons)	Cost at \$36/ton or ~ \$40/Metric ton (\$)	Lime Required (Tons)	(Metric Tons)	Cost at \$19/ton or ~ \$21/Metric Ton (\$)	Total Cost (\$)
Sludge contains 4% solids; vapour effluent treated to pH = 11; liquid effluent treated to pH = 11	.075	.068	2.7	.094	.086	1.8	4.5
Sludge contains 4% solids; vapour effluent untreated; liquid effluent treated to pH = 11	.075	.068	2.7	.080	.073	1.5	4.2
Sludge contains 4% solids; vapour effluent untreated; liquid effluent neutralized to pH = 7	.075	.068	2.7	.042	.039	0.8	3.5
Sludge contains 6% solids; vapour effluent neutralized to pH = 11; liquid effluent treated to pH = 11	.05	.045	1.8	.062	.056	1.2	3.0
Sludge contains 6% solids; vapour effluent untreated; liquid effluent treated to pH = 11	.05	.045	1.8	.052	.048	1.0	2.8
Sludge contains 6% solids; vapour effluent untreated; liquid effluent neutralized to pH = 7	.05	.045	1.8	.028	.025	0.5	2.3

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